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Impact of Diversions and River Regulation on the Flows of the Gunnison River at Black Canyon, Colorado

Gustavo E. Diaz, Jose D. Salas and Gregg E. Farris
(Original Version) November 1994
(Revised Version) February 1996

Colorado State University

Computing Hydrology Laboratory
Hydrologic Science and Engineering Program
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TECHNICAL REPORT No.3

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ABSTRACT

The purpose of this study was to determine the changes over this century in the hydrologic characteristics of the flow regime of the Gunnison River as it passes through the Black Canyon of the Gunnison National Monument (BLCA). While several different factors are responsible for the detected changes, the two main contributors analyzed in this study are the Gunnison Tunnel and the Wayne N. Aspinall Reservoirs. These man-made structures have significantly altered the natural flow regime of the Gunnison River upstream from BLCA by diverting and regulating flows, respectively. The hydrological analysis was conducted using specific statistical techniques for quantitatively describing the changes and differentiating among the system components according to their spatial influence, acting independently or in combination. Results of the study indicated that the mean annual discharge through the BLCA has been reduced by approximately 30 percent from the natural historical levels due to the flow diversions through the Gunnison Tunnel. The shape of the mean annual hydrograph has been drastically altered as a result of the combined effect of the tunnel and the reservoirs. All seasonal characteristics of the natural flow regime have been eliminated, with mean daily flows drastically reduced during the high runoff season and increased during the low runoff season. Low flows through BLCA have been reduced as a result of diversions through the Gunnison Tunnel. Releases from the Aspinall Reservoirs have offset some of the low flow reductions, though this increase has not brought low flows back up to their natural levels. High flows have also been significantly reduced, although this change is primarily due to the reservoirs, with little impact from the tunnel diversions. This study also quantified the extent that the Cimarron River and Crystal Creek, two tributaries of the Gunnison River upstream from BLCA, contribute to restore some of the natural elements of the flow regime that existed prior to the development of the basin. The natural flows discharging from the Cimarron River/Crystal Creek tributaries increased only marginally the variance of the regulated outflows from the Aspinall Reservoirs, yielding a level of flow variability at BLCA that is only a 23 percent of the flow variance under natural conditions.

ACKNOWLEDGMENT

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TABLE OF CONTENTS

APPENDIXES

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

1.1 Purpose and Scope of the Study

The purpose of this study was to determine the changes over the past century in the streamflow characteristics of the Gunnison River as it passes through the Black Canyon of the Gunnison National Monument (BLCA), in the State of Colorado. While many different factors may be responsible for these changes, the two main contributors analyzed in this study are the Gunnison Diversion Tunnel and the Wayne N. Aspinall Reservoirs. These man-made structures, both located upstream from the Monument, have significantly altered the natural flow regime of the Gunnison River by diverting and regulating flows. The changes introduced by these structures on the streamflows were evaluated at the annual, seasonal and daily time levels. In order to discriminate the effects caused by each individual component of the whole system, two separate operational scenarios were analyzed to determine the changes caused by the Gunnison Tunnel alone and then by the Aspinall Reservoirs alone. A third scenario was then evaluated to include the combined effect of both structures, the tunnel and the reservoirs together, since this represents present conditions. In addition, this study quantified the extent that the Cimarron River and Crystal Creek, two main tributaries near the Black Canyon entrance with only negligible level of regulation, contribute to the variability of flow through the canyon. The purpose of this latter effort is to help determine whether these two tributaries are able to restore some of the natural elements of the flow regime that existed prior to the development of the basin.

1.2 Location of Study Area

The Black Canyon of the Gunnison National Monument is located in west-central Colorado in the center of the Gunnison River Basin, as shown in Figure 1. While the Black Canyon itself is about 53 miles long, only the deepest 12 miles of the gorge lie within the National Monument. The Monument boundaries which lie immediately downstream from the Curecanti National Recreation Area, enclose an area of roughly 22 square miles. The entire

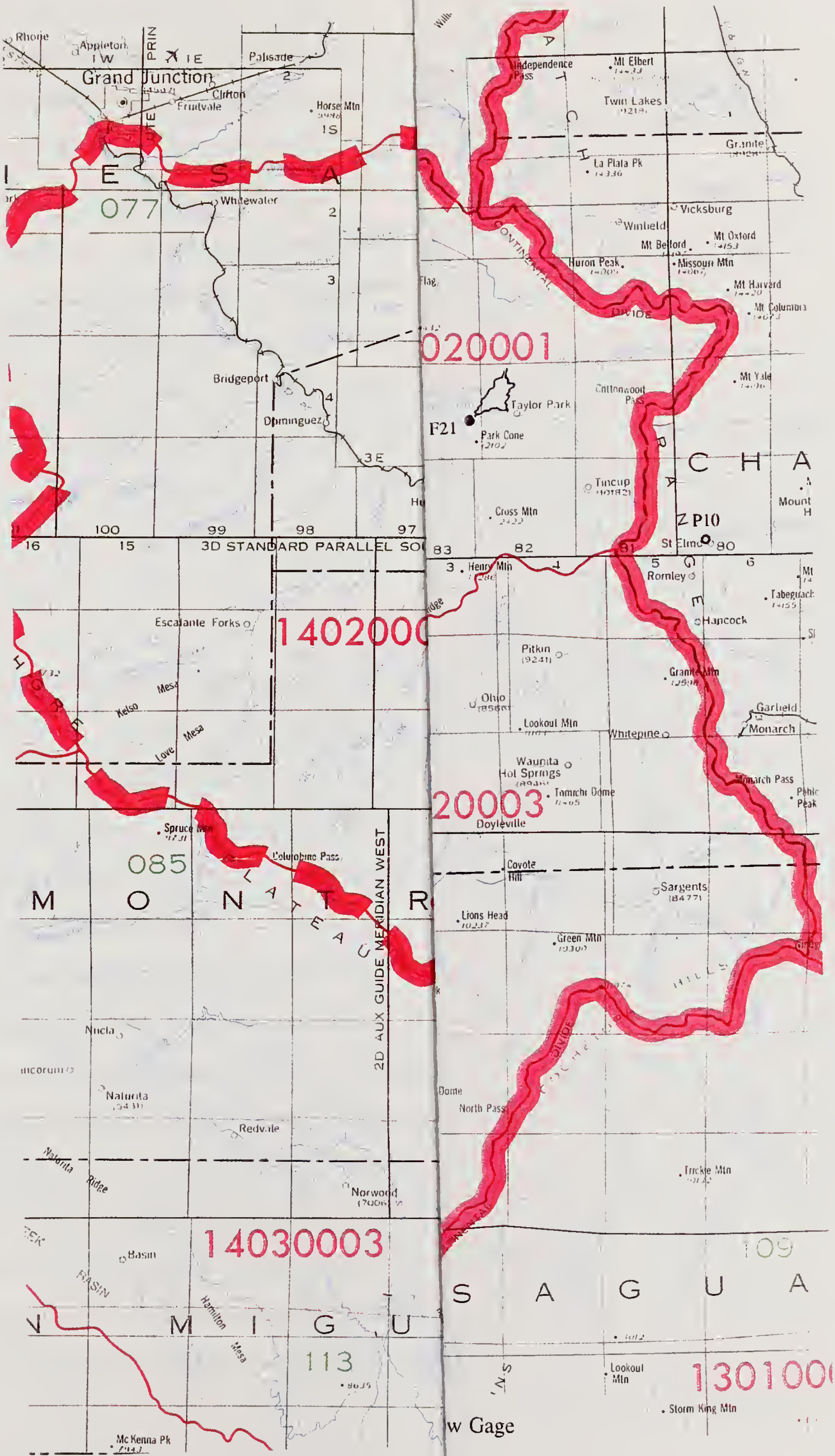

Fig. 1 Gunnison Basin and Black Canyon of the Gunnison River N.M., Location Map

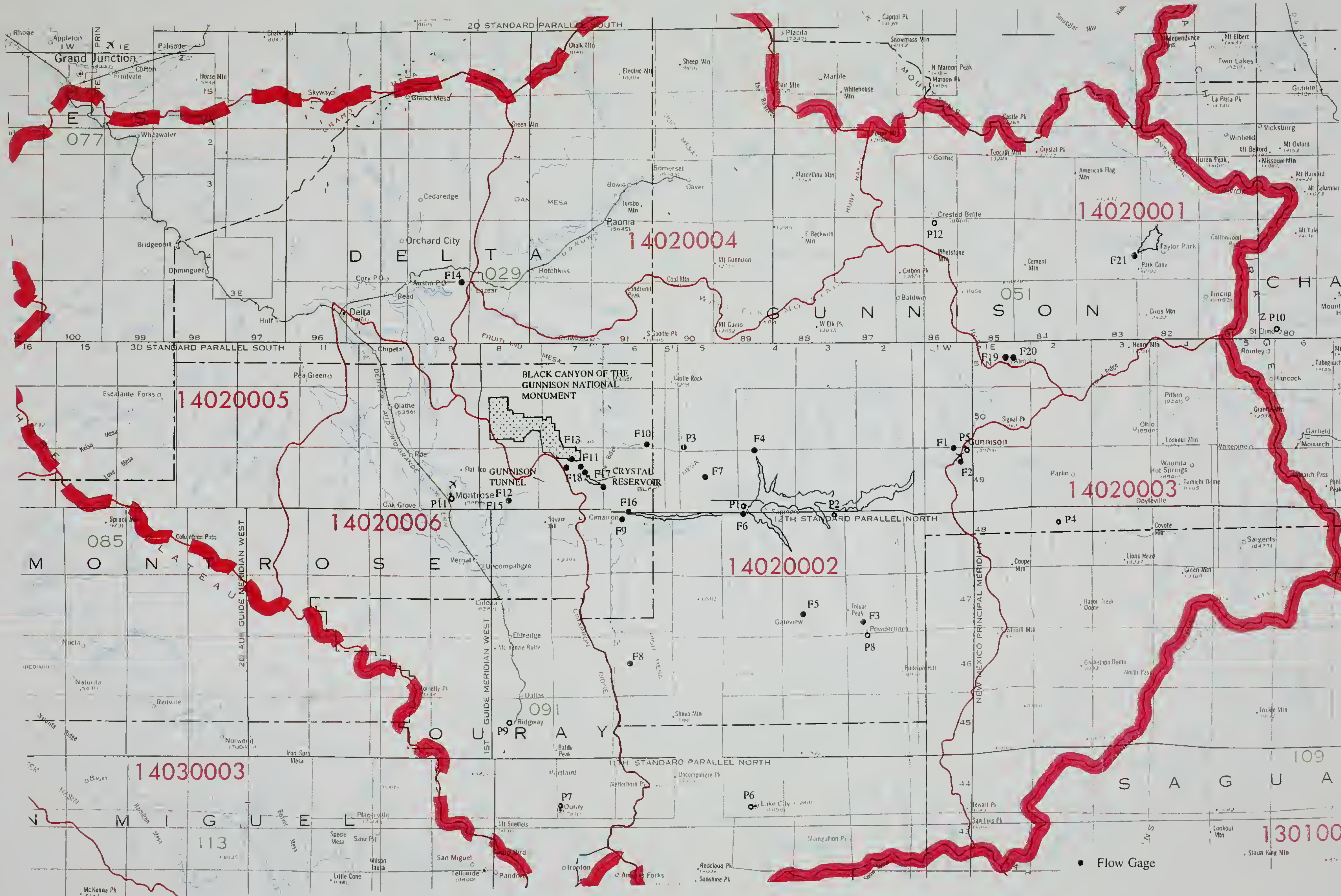

Fig. 1 Gunnison Basin and Black Canyon of the Gunnison River N.M., Location Map

drainage area of the Gunnison River Basin as it enters the Monument is nearly 4,000 square miles. The other main features within the study area, as previously mentioned, include the Gunnison Tunnel, the Aspinall Reservoirs, Taylor Reservoir, the Cimarron River and Crystal Creek, all of which are shown in Figure 1. The Gunnison Tunnel is located on the Gunnison river immediately upstream of the point where the river enters the Black Canyon. The Aspinall Reservoirs, located upstream from the tunnel, actually consists of a series of three reservoirs, namely Blue Mesa, Morrow Point and Crystal reservoirs. The Cimarron River and Crystal Creek, discharging on each side of the Gunnison River, just upstream from the Crystal reservoir, contribute flows to the Canyon with the smallest level of regulation. Distant from BLCA, in the headwaters of the Gunnison Basin, is Taylor Reservoir, the first significant water storage capacity built in the basin. Though not shown in Figure 1, the Gunnison River discharges into the Colorado River and is therefore, an important element of the Upper Colorado region.

1.3 History of Basin Development

The Gunnison River has been carving its way through the rock walls of the Black Canyon for many centuries, creating a very deep gorge which reaches a maximum depth of 2,800 feet. However, development of the basin during the past century has significantly disturbed the natural flow regime through the canyon. A brief account of some of these changes is presented below.

Very early expeditions through the Black Canyon area focused on finding sources for irrigation water for the nearby, arid Uncompahgre Valley (Beidleman, 1959). Information from these research studies led to the construction of the Gunnison Tunnel (see Figure 1) and development of the Gunnison River Diversion Project, now called the Uncompahgre Valley Reclamation Project. Construction of the tunnel spanned the period 1901-1909, and by July 1910, the first diversions through the tunnel were being made. Records of monthly diversions through the tunnel are also published since July 1910. While the Gunnison Tunnel was operational by 1910, the Gunnison Diversion Dam, a 16 foot high weir structure constructed to facilitate the diversion of water into the tunnel, was not completed until 1923.

Operation of the Tunnel was carried out by the U.S. Bureau of Reclamation, originally know as the Reclamation Service, until it was turned over in 1932 to the tunnel owners, the Uncompahgre Valley Water User's association (UVWUA), who continues to operate the tunnel today. The association now diverts from the Gunnison River under the provisions of a 1902 decree, which is one of the most senior rights in the Gunnison Basin. While the 1902 water right allow for diversions through the tunnel up to a maximum of 1,300 cfs, the maximum capacity of the tunnel was determined by recent tests (1987) to be only 1,135 cfs. More recently, a new study related to the Gunnison Tunnel has been presented, named the "AB Lateral Unit Water Supply Study" (HDR, 1989). This project proposes to augment the carrying capacity of the tunnel to its original 1,300 cfs in order to serve a larger irrigation area in the Uncompahgre Valley.

By 1937, Taylor Park Reservoir, with a capacity of 106,200 acre-feet, was constructed in order to store flows in the Taylor River, a headwater tributary of the Gunnison River. Water stored in this reservoir, which is also operated by UVWUA, is released specifically to provide more control of diversions through the Gunnison Tunnel. As a result of this long process, diversions through the tunnel gradually increased from 1910 until about the mid 1940's, at which time they appear to have levelled off.

In the meantime, the Black Canyon of the Gunnison National Monument (BLCA) was established by Presidential Proclamation in 1933, "for the preservation of the spectacular gorges and additional features of scenic, scientific, and educational interest". BLCA went through several boundary changes occurring in 1938, 1939, 1958, 1960, 1976, and 1984. In 1976, a portion of the Monument was designated as wilderness. Then, in 1982, the Colorado Supreme Court awarded reserved water rights to the United States for Black Canyon of the Gunnison National Monument.

The final major development within the Gunnison River basin was the construction of the Aspinall Reservoirs (or Currecanti Unit) by the U.S. Bureau of Reclamation, authorized by Congress in the Colorado River Storage Project Act of 1956. This unit consists of a series of three dams which begin about a half-mile upstream from the BLCA boundary. The primary purpose of this project is to regulate streamflow so that water commitments to the Lower

Colorado River Basin can be satisfied while still meeting water demands in the Upper Basin. Other present uses of water include hydroelectric power genereation, flood control, minimum instream flow releases, recreation in the lakes, etc. The three reservoirs and powerplants continue to be owned and operated by the U.S. Bureau of Reclamation.

Flows in the Gunnison River are primarily stored within the Blue mesa Reservoir, which was the first of the three Aspinall Reservoirs, completed in October 1965. Blue Mesa, also the furthest upstream of the three reservoirs, has a storage capacity of 940,800 acre-feet with a surface area covering 14.3 square miles. The power plant has a total installed capacity of 87 MW. The next reservoir constructed was the Morrow Point reservoir, which lies immediately downstream from Blue Mesa. While storage began in January 1968, power generation did not begin until December 1970. Though Morrow Point reservoir has a storage capacity of 117,000 acre-feet, the primary function of this reservoir is to produce hydropower, especially during periods of peak demand. Thus, the installed capacity of this powerplant is the highest of the three at 120 MW. Because storage in Morrow Point is contained by the walls of the Black Canyon, the reservoir is long and narrow, with a surface area of only 1.3 square miles. The final reservoir to be constructed was the Crystal Reservoir, which was completed in 1976, though storage did not begin until March 1977. Crystal Reservoir is the furthest downstream of the three reservoirs with its dam located less than one mile away from BLCA. The main function of this reservoir is to capture the fluctuating releases from the Morrow Point powerplant and re-regulate them so that releases from Crystal are more uniform. Both the storage capacity of 26,000 acre-feet and the powerplant capacity of 28 MW are considerably smaller than in the other two units. Like Morrow Point, water stored by the Crystal Reservoir is confined by the steep Black Canyon walls, thereby forming a narrow surface with an area of just 0.5 square miles.

Many other developments have occurred within the Gunnison Basin over the past century, such as water diversions and land use changes, which have also affected the flow regime of the river. However, a detailed description and evaluation of all of these smaller changes are beyond the scope of this study.

2.0 STREAMFLOW AND PRECIPITATION RECORDS

Since the entire hydrologic analysis was based upon historical streamflow and precipitation data, this section provides a detailed description of the available records, the stations chosen for each part of the analysis, the period of record selected, and a discussion concerning the reliability of the data.

2.1 Hydrometeorological Records in the Study Area

The streamflow gages found in the study area are listed in Table 1. While most of these gages are managed by the U.S. Geological Survey (USGS), some additional data was obtained from the State of Colorado (Thrush, 1994) and the U.S. Bureau of Reclamation (BuRec) (Ryan, 1994), as indicated in Table 1. Table 1 provides site reference numbers to help locate the streamflow gaging stations in Figure 1. Moreover, Table 1 provides the USGS I.D. number and name, the geographical coordinates, the contributing drainage area, and the period of record expressed in water-years. Because the period of record in which data is available is often discontinuous, the bar diagram in Figure 2 helps visualize the water-years in which data were collected at each station. All streamflow data were recorded as average daily values

With an arrangement similar to the one used for streamflows, Table 2 lists the primary precipitation gages located in the study area, while Figure 3 displays the extent of the periods of record available for each of these stations. All precipitation gages listed are operated by the National Weather Service (NWS), and records were obtained from the Climatological Data Summary published by the National Climatic Data Center (NCDC). Since the NCDC reports values of annual precipitation based on a calendar year, monthly values of precipitation were rearranged to conform to a water-year format and the annual totals recomputed in order to maintain consistency with streamflow records. Total precipitation data were recorded as average daily values. The location of the precipitation gages are also shown in Figure 1, using the site reference number listed in Table 2.

Table 1. Streamflow Gaging Stations in the Study Area

Site No.	USGS I.D.	Station Name	Gaging Station Latitude	Gaging Station Longitude	Gaging Station Ele.(ft)	Drainage Area (mi²)	Period of Record 19__	Period of Record #.WY	Mean Annual Flow (ac-ft)
F1	09114500	Gunnison River near Gunnison	38:32:31	106:56:57	7,655	1,012	11-93	67	550,200.
F2	09119000	Tomichi Creek at Gunnison	38:31:18	106:56:25	7,629	1,061	38-93	56	126,300.
F3	09122000	Cebolla Creek at Powderhorn	38:17:29	107:06:50	8,000	340	37-55	18	73,820.
F4	09122500	Soap Creek near Sapinero	38:33:40	107:19:30	7,790	57	55-66	12	42,350.
F5	09124500	Lake Fork at Gateview	38:17:56	107:13:46	7,828	334	37-93	57	171,200.
F6	09124700	Gunnison Rv blw Blue Mesa	38:27:08	107:20:52	7,149	3,453	63-68	6	818,887.
F7	09125000	Curecanti Creek near Sapinero	38:29:15	107:24:51	7,867	35	46-72	27	23,400.
F8	09126000	Cimarron River near Cimarron	38:15:36	107:32:43	8,631	67	54-93	40	67,360.
F9	09126500	Cimarron River at Cimarron	38:26:28	107:33:13	6,890	209	02-67	8	76,740.
F10	09127500	Crystal Creek near Maher	38:33:05	107:30:20	8,070	42	46-69	18	20,430.
F11	09127998	Gunnison Rv ab Gunn.Tunnel	38:31:34	107:38:56	6,530	3,965	06-65	61	1,285,490.
F12	09127999	Gunnison Tunnel nr Montrose	38:31:37	107:38:57			16-65	50	280,600.
F13	09128000	Gunnison Rv blw GunnTunnel	38:31:45	107:38:54	6,526	3,965	11-93	83	949,200.
F14	09136200	Gunnison River near Lazear	38:46:59	107:50:14	5,090	5,241	62-85	24	1,666,000.
F15	State CO	South Canal / AB-Lateral					60-93	34	327,890.
F16	USBR	Morrow Point Resrvr, Releases				3,637	71-93	23	1,091,257.
F17	USBR	Crystal Reservoir, Releases				3,960	77-93	17	1,251,240.
F18	USBR	Crystal Reservoir, Inflows				3,960	77-93	17	1,251,437.
F19	09112500	East River at Almont	38:39:52	106:50:51	8,206	289	11-93	71	244,200.
F20	09110000	Taylor River at Almont	38:39:52	106:50:41	8,011	477	11-93	83	242,800.
F21	09109000	Taylor Rr blw Taylor Reservoir	38:49:06	106:36:31	9,170	254	39-93	55	142,500.

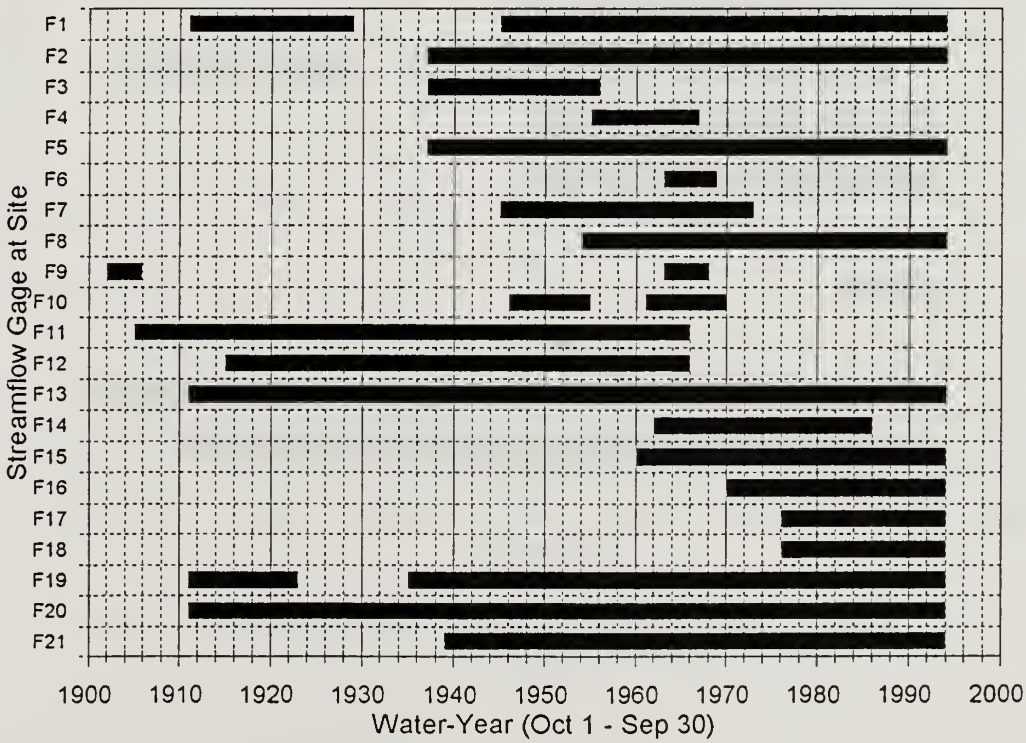

Fig.2 Bar Diagram Showing Periods of Record of Streamflows

Table 2. Precipitation Gaging Stations in the Study Area

Site No.	NWS I.D.#	Station Name	------------- Gaging Station ------------ Latitude	Longitude	Ele.(ft)	Period Record 19'__	# Yrs	Mean Annual Precipit. (in)
P1	794	Blue Mesa Dam, Co.	N38:27:00	W107:20:00	7,630.	66-67	2	
P2	797	Blue Mesa Lake, Co.	N38:38:00	W107:10:00	7,640.	67-92	26	
P3	1609	Cimarron, Co.	N38:33:00	W107:27:00	6,900	51-92	42	
P4	1713	Cochetopa Creek, Co	N38:26:00	W106:46:00	8,000.	48-92	45	
P5	3662	Gunnison 1 N, Co.	N38:33:00	W106:55:00	7,680.	02-92	77	10.49
P6	4734	Lake City, Co.	N38:02:00	W107:19:00	8,670.	48-92	45	
P7	6203	Ouray, Co.	N38:01:00	W107:40:00	7,840.	48-92	45	
P8	6651	Powderhorn, Co.	N38:16:00	W107:06:00	8,090.	64-71	8	
P9	7020	Ridgway, Co.	N38:09:00	W107:45:00	7,000.	82-92	11	
P10	7345	St. Elmo, Co.	N38:42:00	W106:22:00	10,020.	50-53	4	
P11	5722	Montrose, Co.	N38:29:00	W107:53:00	5,790.	00-92	93	9.59
P12	1959	Crested Butte, Co.	N38:52:00	W106:58:00	8,860	09-92	84	22.99

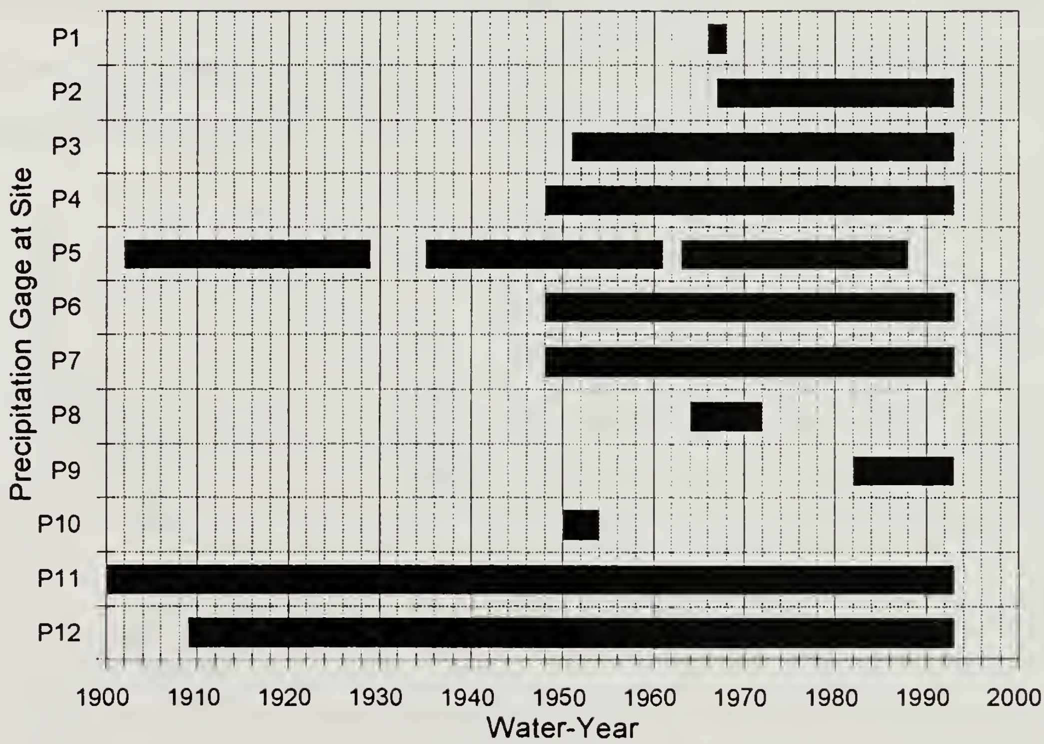

Fig.3 Bar Diagram Showing Periods of Record of Precipitation

Note that the majority of the hydrometeorological records available in the region are of either average length (around 50 years) or short length (less than 25 years). Only one streamflow station and one precipitation station have long records, extending for 82 and 93 years respectively. Based on the operational scenario being analyzed, only a specific subset of gages or a specific period of record was selected. The selected gages and periods of record are described further in the following subsections.

2.2 Streamflow Data for Scenario I: Gunnison Tunnel

Scenario I analyses changes in flow conditions at BLCA had the Gunnison Tunnel were the only structure affecting natural flows in the canyon. Flow data from two gaging stations were used in the analysis, USGS 09127998 (F11) and 09128000 (F13). A schematic of the components of the river system for scenario I is shown in Figure 4. The structures included in the analysis of scenario I are shown with solid lines, whereas those system components excluded from the analysis are depicted with dotted lines. Figure 4 also shows the location of the flow gages, showing with full circles those station actually used in the analysis.

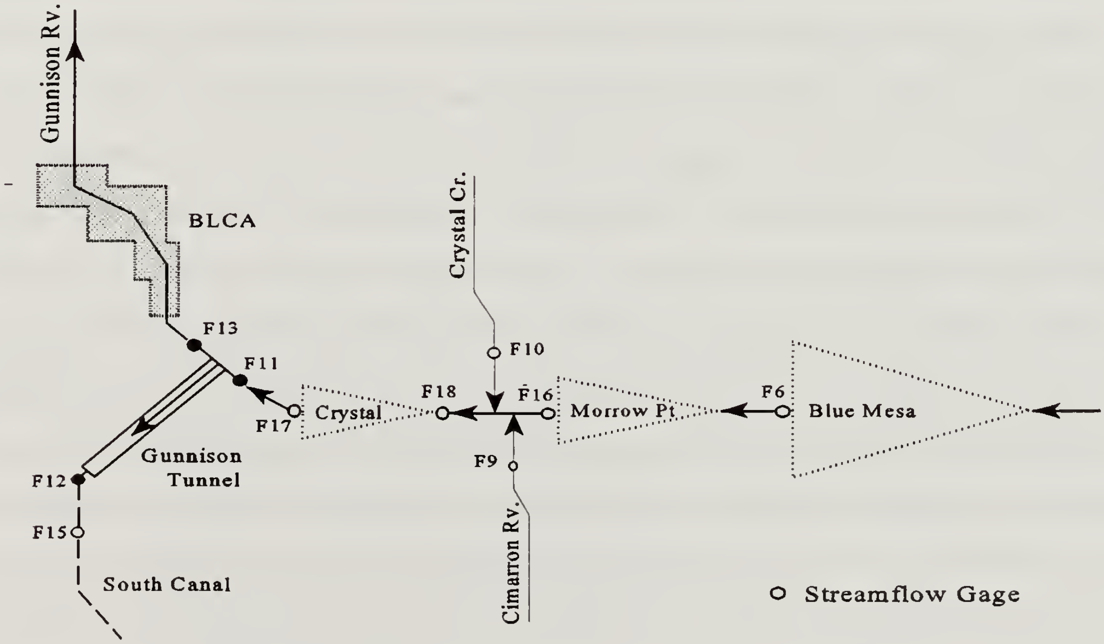

Fig.4 Water System Components for Scenario I

The gage at site F11 measured flows in the Gunnison River immediately upstream from the Gunnison Tunnel, from 1906 to 1965, representing what flows through the Monument would have been had the diversion tunnel never been built. The other gage at site F13, measures flows in the Gunnison River 0.4 miles downstream from the tunnel. This station has been collecting data since water-year 1911 to the present, and therefore represents the actual flows through the Black Canyon. A concurrent period of record at both stations was chosen for this part of the analysis, which includes water-years 1911 to 1965, a total of 55 years. This period was chosen since 1911 was the first complete water-year in which flows were diverted through the Gunnison Tunnel, while water-year 1965 was the last complete water-year before any of the Aspinall Reservoirs began operation. Hence, it does not include any impact to flows in the Gunnison River caused by the Aspinall Reservoirs. However, the selected period is not entirely free of other man caused impacts. Taylor Park Reservoir, located in the headwaters of the basin, has been regulating flows to favor water diversions through the Gunnison Tunnel since 1937. Nevertheless, as demonstrated in Appendix B, the effect of Taylor Reservoir in the flows at BLCA can be considered negligible. In summary, a direct comparison of the flows immediately upstream and downstream from the tunnel over the selected time period should allows us to isolate the effects of the tunnel in the flow regime.

A third station, 09127999 (F12), was also used for this scenario. F12 was utilized to examine the accuracy of the flow data for the other two stations, F11 and F13. F12 recorded flows through the Gunnison Tunnel between 1916 to 1965. By adding the tunnel flows (F12) to the flows in the river downstream from the tunnel (F13), the flows upstream from the tunnel were replicated. This reproduced series of flows were then compared to the measured flow series upstream from the tunnel (F11). The comparison showed that the annual volumes in each case were nearly identical, with the largest difference being much less than one percent. Minimum mean daily flows in each year were also essentially identical, though the maximum mean daily flows differed by about an average of 2 percent each year. As a final check, the mean daily flows for each day between water-years 1941 to 1945 were compared, for which differences in mean daily flows never exceeded one percent. In summary, the data inspection procedure described above guarantees that the data set used to analyze scenario I is reliable.

2.3 Streamflow Data for Scenario II: Aspinall Reservoirs

Scenario II analyses changes in flow conditions at BLCA had the Aspinall Units and Taylor Park Reservoir were the only structures affecting flows in the canyon. Three gaging stations were used to conduct the analysis for this scenario, including USGS 09127988 (F11), 09127999 (F12) and the South Canal gage (F15). A schematic of the components of the river system for scenario II is shown in Figure 5.

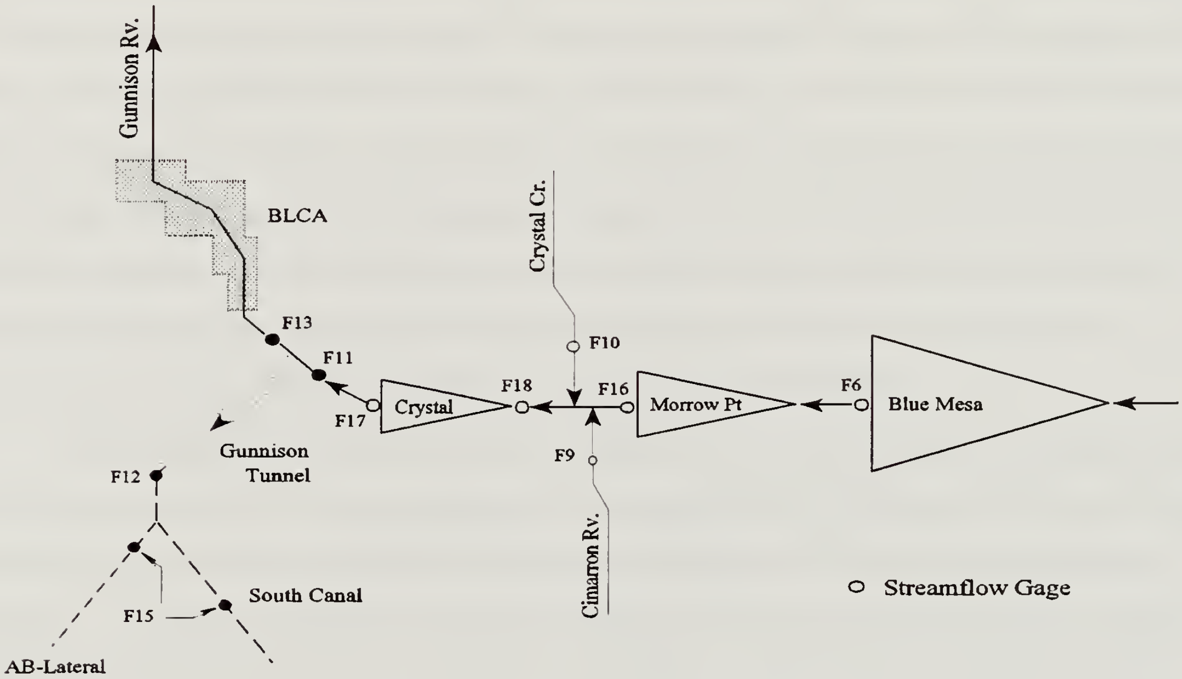

Fig.5 Water System Components for Scenario II

Streamflow data for site F11 was selected over the same time period previously used for scenario I, i.e., between water-years 1911 to 1965. As explained earlier, site F11 is located upstream from the Gunnison Tunnel, hence it represents what flows through the Monument would have been had the tunnel never been built. This time series also does not include the effects of the Aspinall Reservoirs since it ends before any of the three reservoirs began operation. A second streamflow series incorporating the regulation effect of the Aspinall units have to be compared versus the first flow series. This second series should correspond to flows measured also immediately upstream from the Gunnison Tunnel (F11), at

the same location as for the first series. However, only those water-years of data available after the Aspinall Reservoirs began operation have to be considered (after 1965).

Unfortunately, flow records at site F11 were discontinued after water-year 1965, then this gage could only provide data for the first time series. In order to assemble the second series, flow records available downstream from the west portal of the Gunnison Tunnel were used. The flow coming out of the tunnel is separated into two canals: the South Canal, approximately 3600 feet downstream from the tunnel, and the AB-Lateral, located roughly 1700 feet downstream from the tunnel. The State of Colorado (Thrush, 1994) operates a flow gage on each of these two canals. The sum of both records were used to recreate the series of flows in the Gunnison River upstream from the Gunnison Tunnel after water-year 1965, which for simplicity are shown as a single gage in Figure 5, site F15. These combined series of flows therefore represent the actual diversions through the tunnel after 1965, and are equivalent to the flows recorded by station 09127999 until water-year 1965, year on which it was discontinued. Flow records available at site F15 in fact precede 1965.

It should also be mentioned that the subperiod 1966-1970 could not be included into the second time series since the two larger reservoirs, Blue Mesa and Morrow Point, were being filled during those years and releases from these reservoirs do not reflect current release patterns. Therefore, the second series was chosen only between water-years 1971 to 1993, for a total of 23 years, carrying the effect of the reservoirs. Also note that while the two flow series being compared correspond to the same location in the river, two different lengths of records are being used, 55 years and 23 years, for the first and second series respectively. Possible drawbacks of using different records length is discussed further in Section 4.

In order to verify that the flow data from the South Canal/AB-Lateral gages accurately represents the diversions through the Gunnison Tunnel, a comparison was made between the flows recorded at sites F15 and F12. Water-year 1960 was randomly selected from the years in which data for the two gages overlap, and a comparison was made between mean daily flows recorded at each gage. The flows were found to be exactly the same for all but 12 of the 365 days compared, which led to the conclusion that the South Canal/AB-Lateral data combination represents the Gunnison Tunnel flows accurately. Additional inspection of the

data was conducted for the second time series by comparing its flows with releases from Crystal Reservoir. Each day of the water-years between 1991 to 1993 was compared, revealing that flows recreated by summing the two gages were generally within the range ± 20 percent of the flows released from Crystal Reservoir. While releases from Crystal Reservoir are slightly upstream from the Gunnison Tunnel, the local inflow between the two locations could not account for these differences entirely. Nevertheless, considering the accuracy of flow measurements in natural rivers as well as some inconsistencies found in the BuRec database of reservoir releases (see latter discussion in Section 2.5), these differences should not be considered unreasonable.

2.4 Streamflow Data for Scenario III: Combination of Tunnel and Reservoirs

Scenario III analyses changes in flow conditions at BLCA, as impacted by the combined effect of the Gunnison Tunnel and the Aspinall Reservoirs. Basically, scenario III compares present flow conditions at BLCA versus what near natural flow conditions would have been had the basin been kept undeveloped (the effect of Taylor Reservoir and water diversions for irrigation in the headwaters of the Gunnison Basin will still be present). A schematic of the components of the river system for scenario III is shown in Figure 6, highlighting the two flow gages necessary for this part of the analysis, USGS 09127988 (F11) and USGS 09128000 (F13).

The first gage at F11 once again was analyzed between water-years 1911 to 1965, a total of 55 years, and represents flows through the Monument without the effects of either the Gunnison Tunnel or the Aspinall Reservoirs. The second gage at F13, was analyzed between water-years 1971 to 1993, a total of 23 years, and therefore, includes the combined impact by both the tunnel and the reservoirs. Verification of the data from these two gages has already been explained in the previous two sections. Additional verification was deemed unnecessary.

2.5 Streamflow Data for Scenario IV: Cimarron River/Crystal Creek

Scenario IV constitutes a special portion of the study directed to define the relative contribution of Crystal Creek and the Cimarron River to the variability of flows at BLCA.

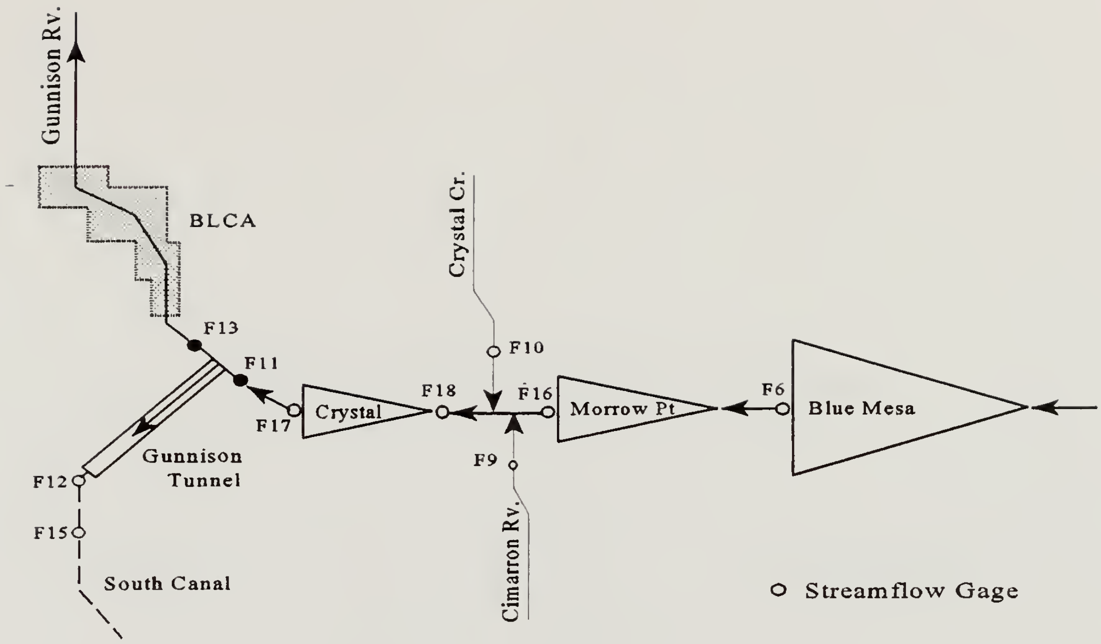

Fig.6 Water System Components for Scenario III

These two tributaries of the Gunnison River, located between Morrow Point Dam and Crystal Dam, generate most of the incremental local flow between the two structures, encompassing a contributing drainage area of nearly 323 square miles. This drainage area also includes some other minor tributaries. The schematic in Figure 7 shows the system components used for this scenario, the catchments of interest between the two dams and the streamflow gages used in the analysis.

As displayed in Figure 2, flow records for Crystal Creek (F10) and the Cimarron River (F9) are of very short duration to be used in the analysis. Therefore, it was necessary to estimate the incremental local flows between the two dams using an indirect approach based on the series of daily inputs and outputs from the Aspinall reservoirs. The Bureau of Reclamation maintains a complete database of inflows and outflows from the Aspinall Units since the first powerplant began operation in 1965 to the present. The time series of incremental local daily flows was assembled between water-years 1978 to 1993, a total of 16 years. Water-year 1978 was chosen to begin the analysis since it is the first full water-year after the last powerplant (at Crystal) began operation.

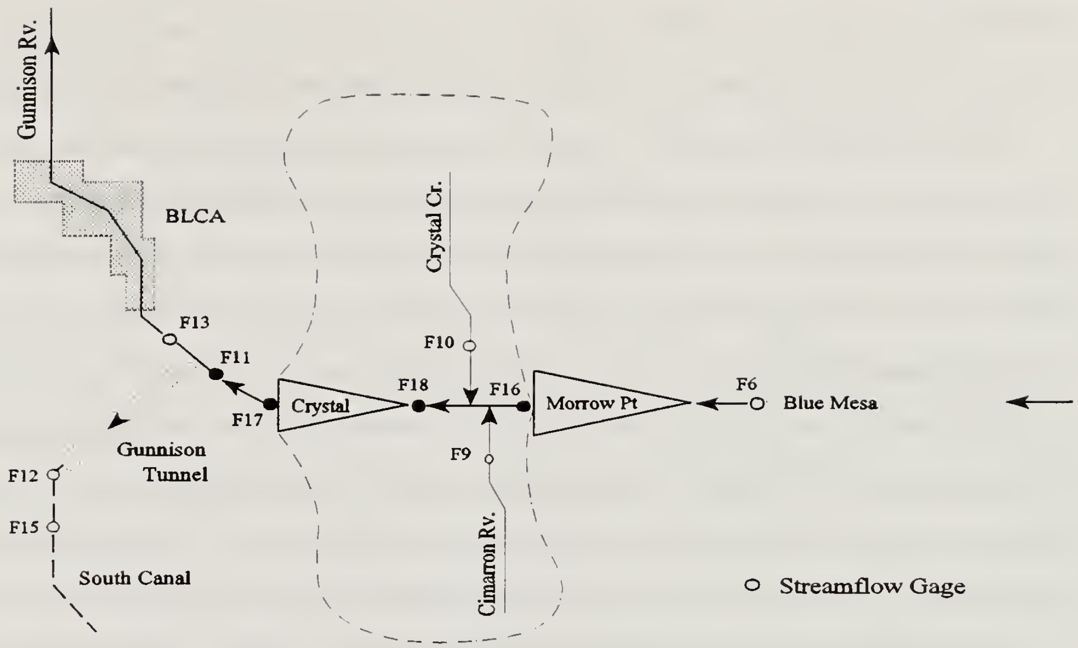

Fig.7 Water System Components for Scenario IV

Several attempts were made to estimate the incremental inflows. The first attempt consisted in subtracting Morrow Point releases from Crystal releases, and at the same time accounting for changes in water storage at Crystal reservoir. Net evaporation from Crystal reservoir was estimated negligible. A second attempt involved subtracting Morrow Point releases directly from Crystal inflows. This last approach should yield results similar to the first approach since Crystal Dam impounds a small lake. In fact, there is no actual gage of the Crystal inflows as indicated in Figure 7. Crystal inflows are generated by the BuRec using measured data from the reservoirs and then adjusting the database in order to preserve water balance among the three reservoirs (Ryan, 1994, personal communication). A third attempt was also made repeating the procedures described above for attempts one and two but this time using databases that were not previously adjusted by the BuRec, namely powerplant (and other) releases from Morrow Point and Crystal reservoirs.

All three computational attempts yielded some obviously erroneous values of the incremental local inflows, mostly in the form of negative inflows. A close examination of the (adjusted) BuRec database revealed the origin of these inconsistencies, with reservoirs inflows and outflows showing sporadic negative values. Whereas the BuRec monthly averages of inflows and outflows are consistent and satisfy water balance at the reservoirs, the same database at the daily level have obvious deficiencies. As a compromise and after reviewing the results from the three attempts, we chose to adopt the BuRec series of side inflows to Crystal Reservoir, denoted as SID_CFS, as the series that best represents the incremental local inflows between Morrow Point Dam and Crystal Dam. The negative values found in this series (around 1% of the total number of values) were all concentrated during 1989 and 1990. These two years of side inflows were replaced entirely by inflows obtained by subtracting Crystal total inflows from Morrow Point releases. Despite all the inconsistencies described above, we believe that the chosen time series still provides a reasonable representation of the incremental local inflows between the two dams.

2.6 Precipitation Records

Only three of the twelve precipitation stations listed in Table 2 contained long enough records as needed for this study. The gage with the longest record (since 1901), NWS 3662 (P5) - Gunnison 1N, is located at the City of Gunnison, ideally placed in the middle of the study area. The second gage, NWS 5722 (P11) - Montrose, is located roughly 12 miles west of the western boundary of the Gunnison Basin. The third station, NWS 1959 (P12) - Crested Butte, is located on the northern edge of the basin, at a much higher elevation than the other two stations. Thus, total annual precipitation for the latter station is consistently larger than at the two lower elevation stations. Figure 1 shows the exact location of all the precipitation stations.

2.7 Changes in Hydroclimatological Conditions

Hydroclimatic records within the study area were examined for possible fluctuations or changes in precipitation and surface flows that could have taken place during the study period. The literature contains evidence of changes in water yield in other regions of the

Upper Colorado Basin, see for instance Yevjevich (1961). The consistency of hydrologic data can be tested using a direct graphical method named the double-mass curve. Given two variables X and Y occurring jointly, the double-mass curve is constructed by plotting cumulative observations of the X's variable versus the cumulative values of the corresponding Y's. In the case of the Gunnison Basin, a double-mass curve analysis was conducted between total annual precipitation at Gunnison (station 3662 - P5), and the Gunnison River flows near the entrance to BLCA (station 09127998 - F11). The analysis was carried out for the period 1912 to 1965, with some missing years as indicated by the precipitation record. As explained earlier in Section 2.2, flow records for the period 1912-1965 are exempted of any reservoirs regulation effect or tunnel diversions. The double-mass curve for the Gunnison Basin is shown in Figure 8.

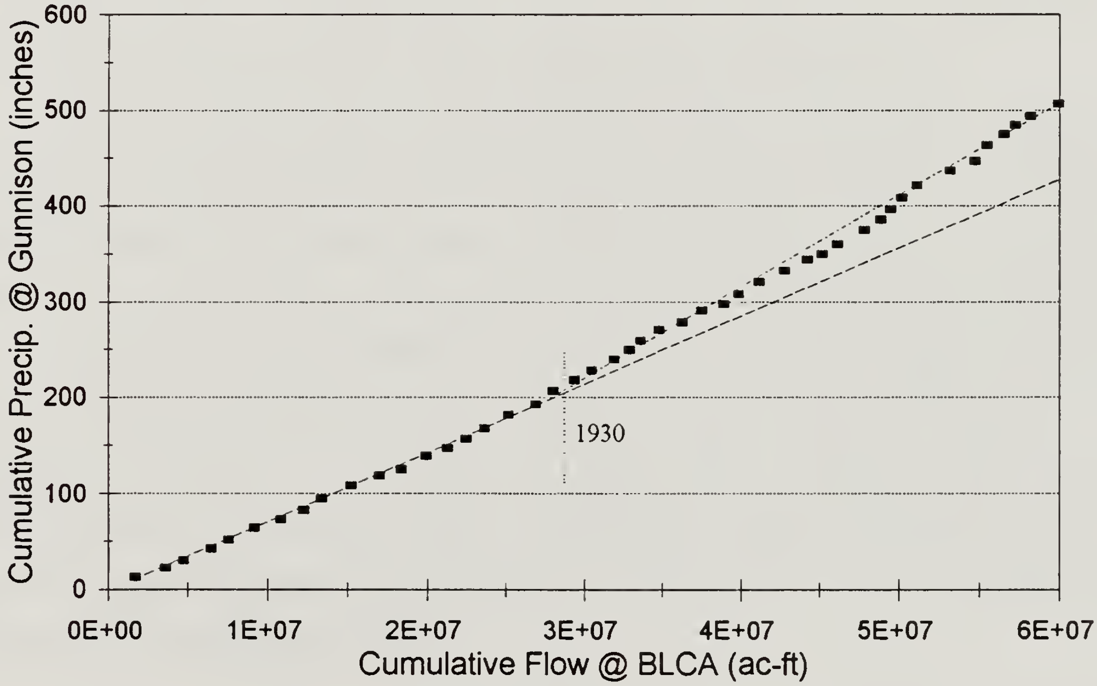

Fig.8 Changes in Hydroclimatological Conditions, Double-Mass Curve

Figure 8 shows a discontinuity in the slope of the rainfall-runoff relation around water-year 1930. The 1930 date was confirmed by repeating the double-mass analysis using another precipitation station (Montrose, P11). Immediately the question arises whether there

was a significant change in meteorological conditions that could have triggered the change in surface runoff. Records from the three precipitation gages cited in Section 2.6 were examined for a downward shift after water-year 1930. While each of these gages indicated a reduction in precipitation after 1930, ranging from one to seven percent, none of these shifts were found to be statistically significant.

In addition to natural changes, man-made causes were examined as well, primarily the increase in water surface diversions in the Upper Gunnison Basin after 1930. Unlike the Gunnison Tunnel diversions, some of these diverted flows would eventually be returned to the river upstream from Black Canyon, although the volume of water not returned could become significant. While flow records were not available to examine the actual volumes diverted within the river basin, water rights records do indicate that rights to significant volumes of water were granted for various purposes, such as irrigation, after water-year 1930. In other words, it is speculated that changes in land-use practice in the basin may have been a significant factor in the reduction of annual flows through BLCA.

A brief search was also made to determine whether this downward shift in annual volumes occurred at other locations within the region. Upstream, at the City of Gunnison, the annual volumes in the Gunnison River were found to shift downward by 21.4 percent between the water years 1911 to 1928 and 1945 to 1993. Downstream from the Gunnison River, the virgin flows of the Colorado River at Lee Ferry, Colorado, exhibit two marked periods of wet and dry subperiods during the period of 1914 to 1965 which cannot be explained by inconsistencies in the data (Salas and Boes, 1980). Though a single cause has not been pinpointed, this downward shift in annual volumes around 1930 appears to have occurred throughout the Upper Colorado region. It is important to bear this finding in mind during the analysis of scenarios I to IV.

3.0 HYDROLOGICAL IMPACT OF THE GUNNISON TUNNEL

Scenario I analyses changes in flow conditions in the BLCA caused by diversions through the Gunnison Tunnel. As described in Section 2.2 of this report, flows in the Gunnison River just upstream from the tunnel are compared with flows immediately downstream from the tunnel over the same time period. This time period includes the 55 years between water-years 1911 to 1965. The investigation of the hydrological data includes several time intervals of analysis, from the annual to the daily series of flows, including annual series of maximum and minimum daily flows. The reader is referred to Appendix B: Effect of Taylor Park Reservoir, to complement the findings presented in this section. Methods and equations used to conduct the hydrological analysis for this study are included in Appendix I.

3.1 Water Demand Through the Gunnison Tunnel

Figure 9 shows the amount of water diverted through the Gunnison Tunnel year after year since it began operation in 1911. Water demand increased significantly during the first 20 years of operation. Later, from 1930 to 1965, the demand continued increasing but at a

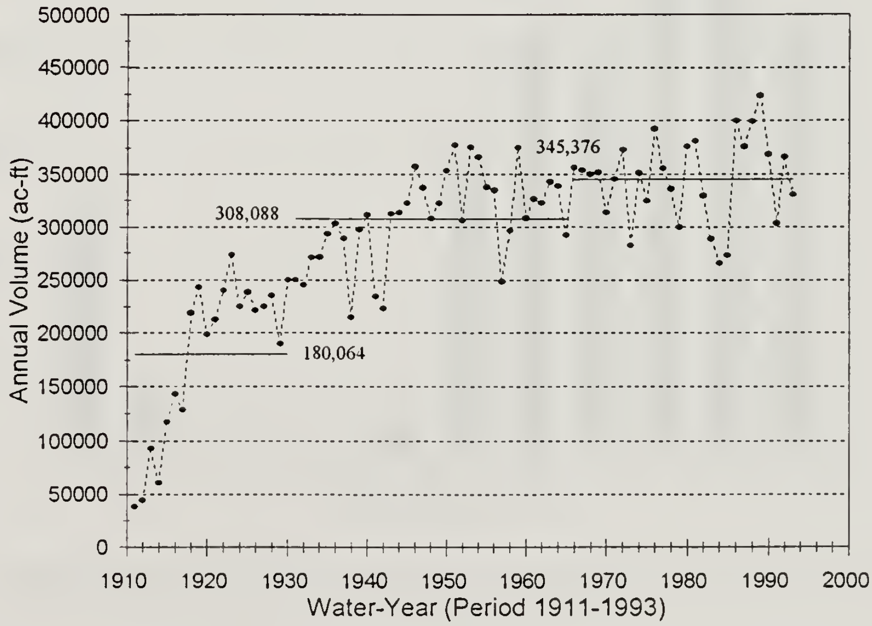

Fig.9 Gunnison Tunnel Diversions, Annual Series

lower rate than in the previous 20 years. Since 1965 the demand reached an asymptotic level around 345,400 acre-feet per year, which represents the present average level of tunnel diversion.

In order to distinguish how diversions through the Gunnison Tunnel are distributed over a regular year, the average volume of water diverted through the tunnel was calculated for each month of the year during the period 1911-1993. These monthly volumes are shown in Figure 10 along with the percentage of the annual volume for each month. Notice that from November to March (non-irrigation season), diversions through the tunnel account for only 2.4 percent of the annual diversion volume. The irrigation season runs from April to October, with the maximum monthly diversion occurring during August with 18.4% of the total. This last percentage is equivalent to a continuous diversion rate of 1,068 cfs during the month, close to the 1,135 cfs reported as the maximum conveyance capacity of the tunnel.

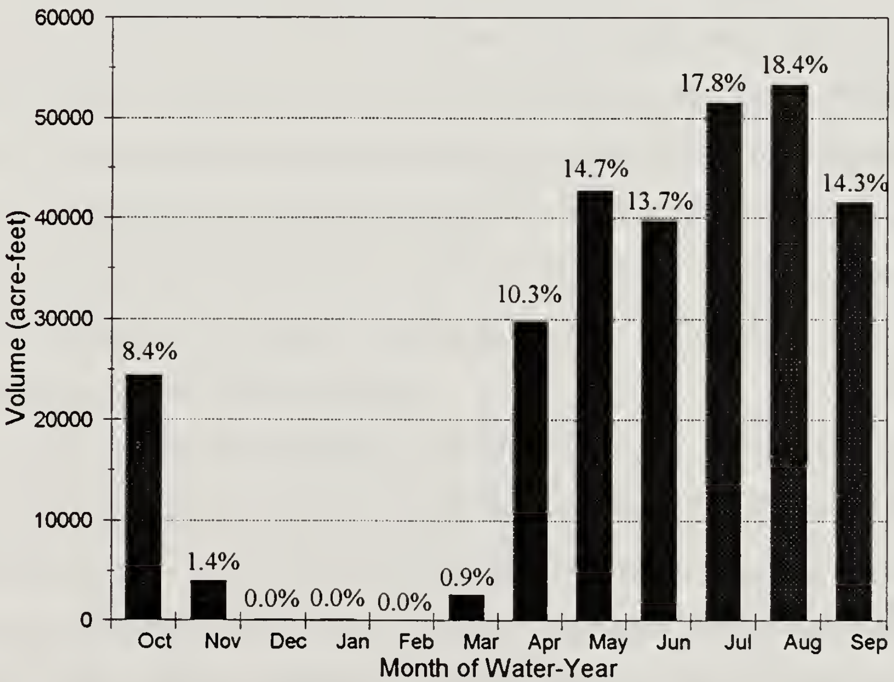

Fig.10 Monthly Distribution of Water Diversions Through the Gunnison Tunnel

3.2 Impact of Tunnel Diversions on the Series of Annual Flows

Beginning the analysis at the annual level, the time series of annual discharge in the Gunnison River immediately upstream and downstream from the tunnel are plotted in Figure 11a and 11b respectively. The mean annual volume above the tunnel was found to be 1,269,400 acre-feet over the period 1911-1965, while the mean below the tunnel was 1,007,700 acre-feet. Their difference indicates that the tunnel withdrew an average of 261,700 acre-feet of water, roughly 21 percent, from the Gunnison River each water-year over the whole period. However, this fraction increases to 27 percent when considering the sub-period between 1931 to 1965, which does not include the early years of the operation of the tunnel when diversions were lower. Moreover, when considering the present level of tunnel diversion of 345,400 acre-feet (average since 1965), that same fraction increases to 30.5 percent.

The other important feature found in both graphs of Figure 11 is the downward shift in annual volumes that occurred in the Gunnison River around 1930. Both statistical and graphical tests were performed, including the Mann-Whitney test, the S-S plot and the double mass curve, all of which confirmed that the shift is statistically significant. While part of the downward shift in the flow series downstream from the tunnel should be attributed to an increase in tunnel diversions after 1930 (see Figure 9), the flow series upstream from the tunnel is still shifted downward by about 24 percent. Therefore, other factors beside the tunnel must be responsible for this shift. See Section 2.7 for further details concerning changes in hydrological conditions in the basin.

Even though the effect of the tunnel is to reduce the mean of the annual discharge, the standard deviation of the annual volumes actually increased from 377,473 ac-ft^2 to 428,072 ac-ft^2, a 13.4 percent change. The increase in the standard deviation comes as a result of the tunnel diverting proportionally more water during dry years than what it does during wet years. In other words, irrigation demand is correlated with the type of water-year, the drier the year the more water is being diverted to satisfy the irrigation demand. This introduces an increase in the dispersion or variation of the annual volumes with respect to its central value.

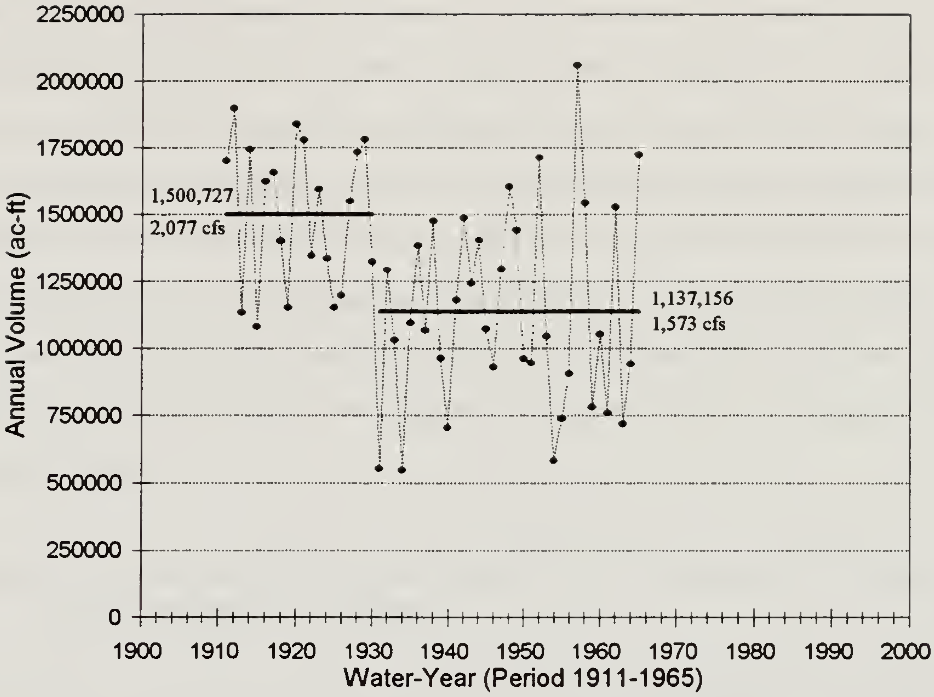

Fig.11a Annual Flows at BLCA, Without Diversions

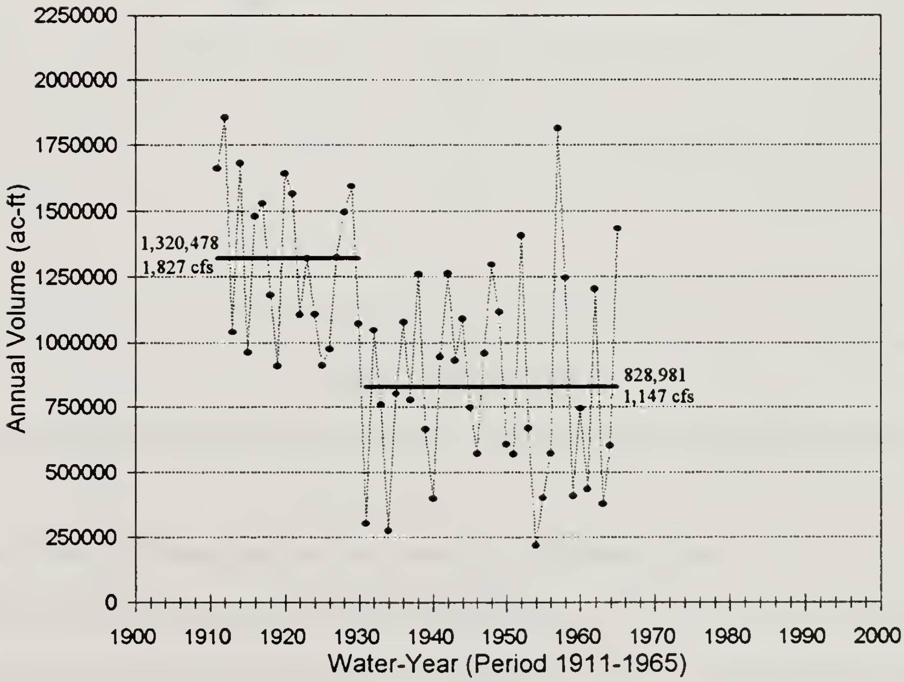

Fig.11b Annual Flows at BLCA, With Diversions

In addition, the quantiles for the annual volumes both upstream and downstream from the tunnel were calculated and plotted in Figure 12. The reduction in annual volumes caused by diversions through the tunnel is evidenced by the difference between the two curves. The result is that any given level of annual flow through the Black Canyon occurred less frequently due to tunnel diversions than would have occurred without the presence of the tunnel. For instance, if no tunnel diversions had taken place, an annual volume of 1.5×10^6 acre-feet would have had a recurrence interval slightly above 3 years (in near natural conditions). However, with tunnel diversions occurring, that same level of annual volume should be expected to occur only once every six or seven years, that is, it has practically doubled its return period.

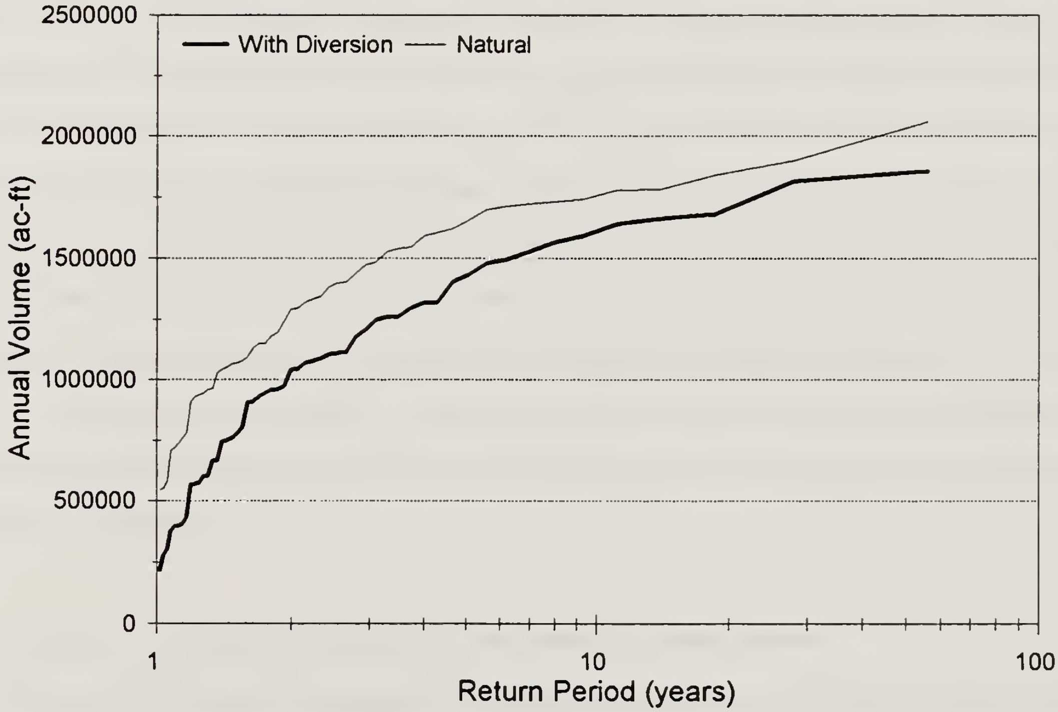

Fig.12 Change in Annual Flow Quantiles at BLCA Due to Tunnel Diversions

3.3 Impact of Tunnel Diversions on the Series of Extreme Flows

The annual series of extreme flows are constituted by the maximum or minimum mean-daily flows within each water-year (only one value per year). Extreme mean-daily flows should not be mistaken with maximum or minimum instantaneous flows.

3.3.1 Annual Maximum Flows

Comparing the two series of maximum mean-daily flows upstream and downstream from the tunnel indicates that the tunnel has little effect on the high peaks, causing the mean of these mean-daily peaks to be reduced by only 4.4 percent. The downward shift in annual volumes that occurred around water-year 1930 also appears in each of the series of maximum flows. The same statistical and graphical tests were performed to confirm that each shift was statistically significant. Based on the finding for maximum mean-daily peaks, it can be concluded that even a less significant change should be expected for the series of maximum instantaneous peaks (not included in our analysis).

3.3.2 Annual Minimum Flows

In contrast to the series of maximum flows, the series of annual minimum flows is severely affected by diversions through the Gunnison Tunnel, as illustrated in Figure 13. Comparing the two annual series of minimum flows upstream and downstream from the tunnel for the period 1911-1965 indicates that the average low-flow was reduced from 349 cfs to 49 cfs as a result of tunnel diversions. Even more dramatic, the mean was reduced from 301 cfs to 15 cfs for the sub-period between 1931 to 1965. Tunnel diversions caused the minimum flow in the river to drop to zero during three separate years over the period 1911-1965, whereas under natural conditions, the minimum annual flow in the river never would have dropped below 100 cfs. Finally, a downward shift also occurred in each of the series of minimum flows around 1930, as shown in Figure 13, which were confirmed to be statistically significant.

3.4 Impact of Tunnel Diversions on the Series of Daily Flows

In order to evaluate the impact of the tunnel diversions in the BLCA at the daily level, two series of mean-daily flows from each day of the water-years between 1911 to 1965 were selected. This portion of the analysis focuses on the basic statistical descriptors of the marginal distributions of mean-daily flows. Daily flows series are non-stationary in nature as a consequence of the periodicity in the series parameters.

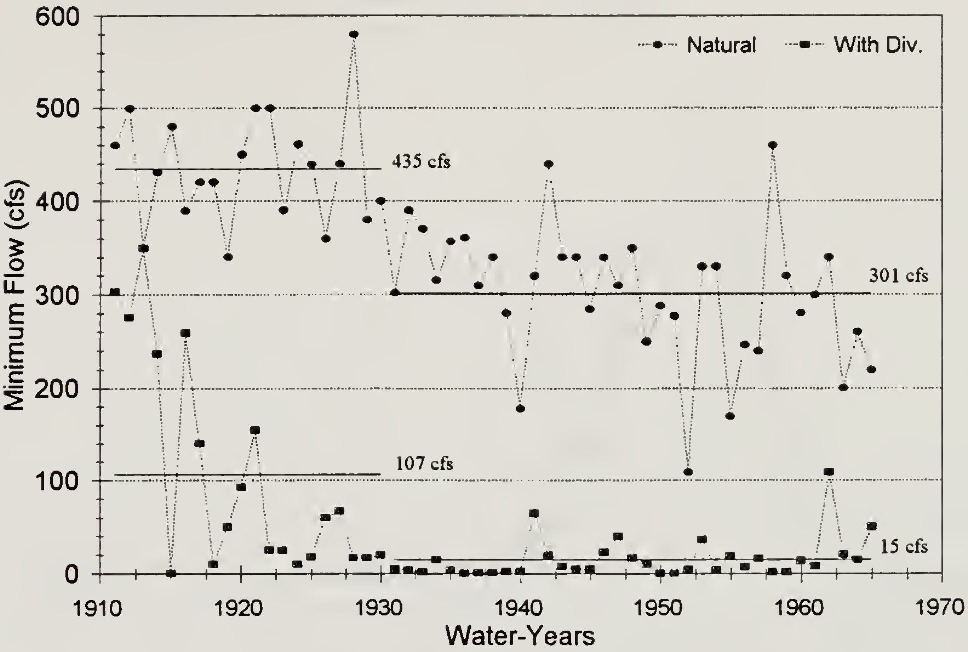

Fig.13 Annual Minimum Flows at BLCA, With and Without Diversions

3.4.1 Basic Statistics of Mean-Daily Flows

To begin with the analysis, the average of the mean-daily flows (also termed daily means) were computed for each of the 365 days of the water-year as plotted in Figure 14. The shape of the mean-annual hydrographs indicate that surface runoff in the Gunnison Basin is primarily dominated by snowmelt, with the peak of the hydrographs occurring from early April through the end of August. All curves are relatively smooth, with no visible effect of strong convective storms altering the hydrographs.

The graph shows three curves, one hydrograph for near natural conditions (labeled Natural) and two hydrographs representing impacted conditions. The higher of the two affected hydrographs (W/Diversions 1911-1965) can be compared directly with the natural conditions curve, since both correspond to the same time period. Just as with the mean-annual volumes, mean-daily flows are lower downstream from the tunnel than upstream due to the tunnel diversions, with a 21% decrease in total annual flow during the period. However, Figure 14 shows us how these differences are distributed throughout the water-

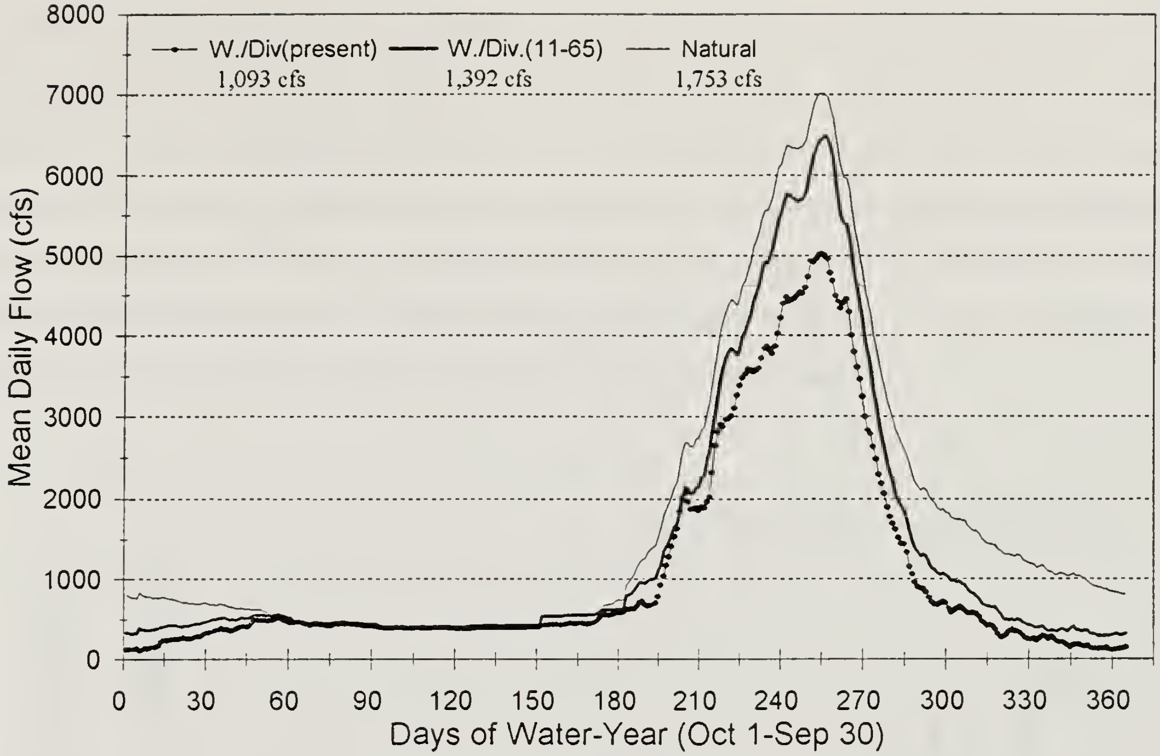

Fig.14 Daily-Mean Flows at BLCA, With and Without Diversions

year. During the non-irrigation season, roughly December through March, daily means above and below the tunnel are practically identical since little or no water is being diverted. Hence, the depletion takes place outside this period. The most severe depletions occur by the end of the summer, with up to nearly 70% decrease in daily means. The third hydrograph (labeled W./Div. present), is an estimate of what flow conditions in BLCA would be at the present had the tunnel were the only structure altering flows in the river nowadays. This hydrograph is noticeably lower than the one computed for the period 1911-1965. The reason is two fold: (i) tunnel diversions since 1965 are substantially larger than what they were before 1965 (see Figure 9), and (ii) there has been a decrease in water-yield in the basin after 1930 (see Section 2.7). When comparing the mean-annual flow corresponding to this last hydrograph (1,093 cfs), with the same statistic for the annual flows at BLCA without diversions (natural) for the period 1931-1965 (1573 cfs, see Fig.11a), the present level of tunnel depletions would amount to 30.5%, significantly larger than the 21% obtained for the period 1911-1965.

Similarly, the periodic standard deviations were found for each day of the water-year. As with the daily mean flows, the standard deviations of the flow upstream and downstream from the tunnel were the same during the non-irrigation season. During the rest of the year, though, the tunnel increases the deviation from the daily means. The cause of this increase in variability has been explained earlier in Section 3.2. Instead of the standard deviations, we opted to present in Figure 15 periodic functions of the coefficient of variation Cv, a non-dimensional estimate of flow variability displaying the same behavior. Cv is computed as the ratio between the periodic standard deviation and the periodic mean.

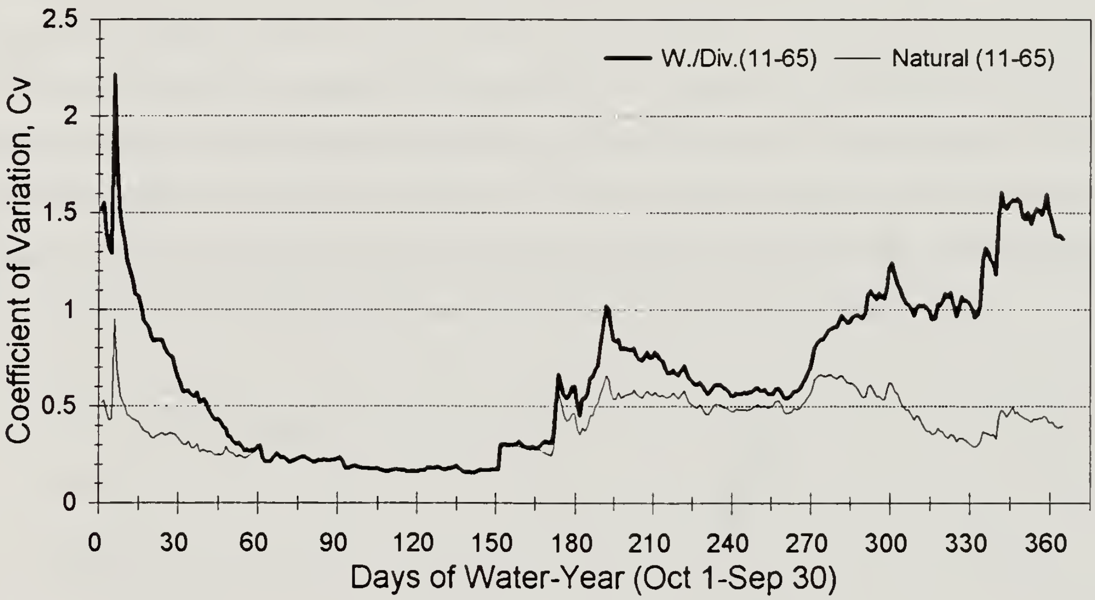

Fig.15 Daily Coefficient of Variation, With and Without Diversions

Daily correlation of flows was measured by finding the daily autocorrelation coefficient for each day of the water year. Again, because most of the river flow is generated by snowmelt and return of subsurface flow, the correlation of flows from one day to the next are naturally very high. The average value of the autocorrelation coefficient was found to be greater than 0.9 for all but a few days of the water-year both upstream and downstream from the tunnel. Diversions through the tunnel appear to have had very little effect on the correlation of flows between two successive days.

3.4.2 Marginal Distributions of Daily Flows

The marginal probability distribution of daily flows are studied without removing the periodicity in the mean and standard deviation of the daily flows (i.e., study of the original data). On the other hand, given the length of the database (55 years of data), fitting probability distributions to the 365 marginal distributions was not deemed necessary. Only empirical marginal distributions were computed for each day of the water-year, from where specific frequencies of occurrence were selected and plotted in Figure 16. The marginal distribution curves plotted in Figure 16 correspond to near natural conditions in the river, or what the distribution of flows through BLCA would have been without the tunnel diversions. They were built with flow values for each day of the water-year corresponding to 5%, 25%, 50%, 75%, and 95% non-exceedance probabilities. For instance, an ordinate of the line representing the 95% non-exceedance probability indicates the flow level for which 95% of the flows on that specific day did not exceed, or in other words, that only 5% of the flows were greater than that particular flow level over the whole period of record. Additionally, the curve of the mean daily flows is shown in the same graph with a thicker line.

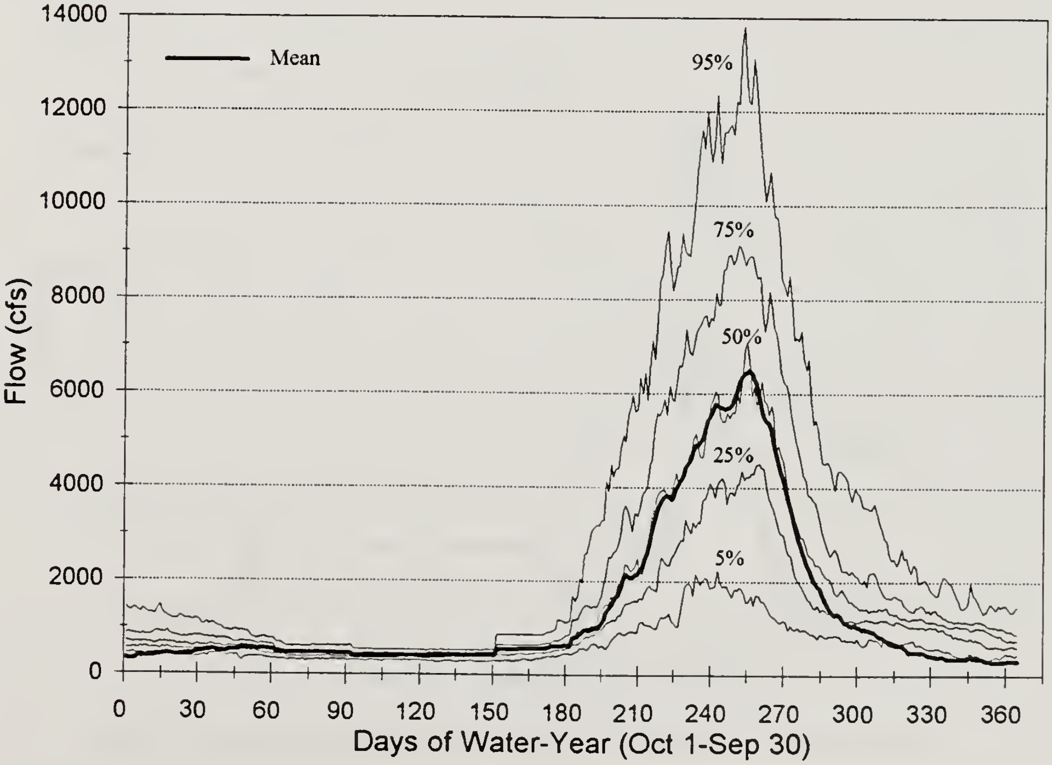

Fig.16 Marginal Distributions of Daily Flows at BLCA, Without Diversions

The marginal distribution of mean-daily flows are typically asymmetrical. This is also true for the Gunnison River as depicted in Figure 16, where the degree of separation between the median (50%) curve and the mean curve is an indicator of the level of asymmetry of the marginal distributions. The examination of the two constructed sets of marginal distributions, with and without tunnel diversions, have shown that once again, the tunnel has no effect on the flow distribution during the non-irrigation season. During the rest of the year, though, the tunnel lowers each of the distribution curves. For the high non-exceedance probabilities (above 50%), the down-shifting of the distribution is relatively small, while for the low non-exceedance probabilities (below 50%), the change is very significant. To illustrate this point, a comparison is shown in Figure 17 of the flow levels with and without tunnel diversions for a non-exceedance probability of 5% (low flows). These curves clearly illustrate that, except during the non-irrigation season, tunnel diversions cause that specific flow percentile to be significantly lowered, even reaching close to zero values never experimented on natural conditions. Even more dramatic differences can be detected for non-exceedance probabilities less than 5%.

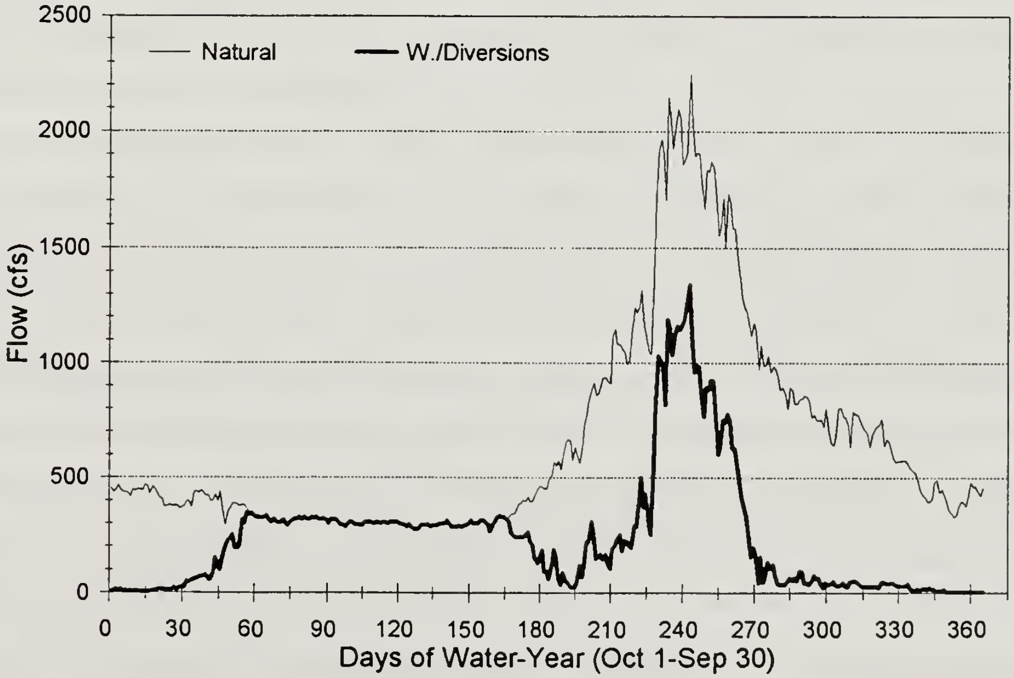

Fig.17 Comparison of 5% Percentile of Mean-Daily Flows at BLCA

3.4.3 Magnitude and Frequency of Daily Flows

This section examines the relationship between the magnitude and frequency of mean-daily flows in the Gunnison River both upstream and downstream from the Gunnison Tunnel during the period 1911 to 1965. The section is comprised of three frequency analysis tools:

a. Flow Duration Analysis

Flow duration analysis (FDA) estimates the percentage of time that any given flow in a stream was equalled or exceeded over a historical period. While a flow duration curve (FDC) provide a sense of the availability (frequency) of flows during a given time span, it does not account for the actual sequencing or progression of the flows in the natural series. Initially, the FDA was conducted following the customary "period-of-record flow-duration curve" methodology in which all of the daily flows from the 55 years study period were combined and ranked from the highest to the lowest value. The percentage of time that any given flow in this series is exceeded is estimated using the Weibull plotting position. A drawback of this approach is that when one or two extremely high (or low) flows have occurred over the period of record, the high (or low) flow end of the FDC is significantly influenced. This is a common weakness of the traditional FDA since it is often highly sensitive to extreme flows associated with the period of record chosen.

After some experimentation with the Gunnison River data, and for the reasons exposed above, it was decided to use an alternative approach for FDA introduced by Vogel and Fennessey (1994). This new approach, termed the "mean or median-annual flow-duration curve", is based on considering *n* individual FDC's, each corresponding to one of the individual *n* years of record. In order to summarize the year-to-year variability in those *n* annual FDC's, two measures of central tendency of the annual FDC's are computed, the mean and the median-annual FDC. In other words, for each exceedance probability, the mean and median values of discharge are computed using the *n* individual annual FDC's. Note that the annual FDC's does not represent any specific water-year, it is just a representation of the distribution of daily streamflows in a "typical" or median hypothetical water-year at the selected river site. Figure 18 provides a comparison of the median-annual FDC's upstream and

downstream from the Gunnison Tunnel. In addition, and with the purpose to compare the two FDA approaches cited above, the period-of-record FDC for the natural conditions only is also shown (dashed line). Note also that the median-annual FDC's tend to approximate the period-of-record FDC except for exceedance-probabilities below 20%. This finding confirms our earlier discussion about the influence of abnormally wet (or dry) hydrologic events in the shape of the FDC.

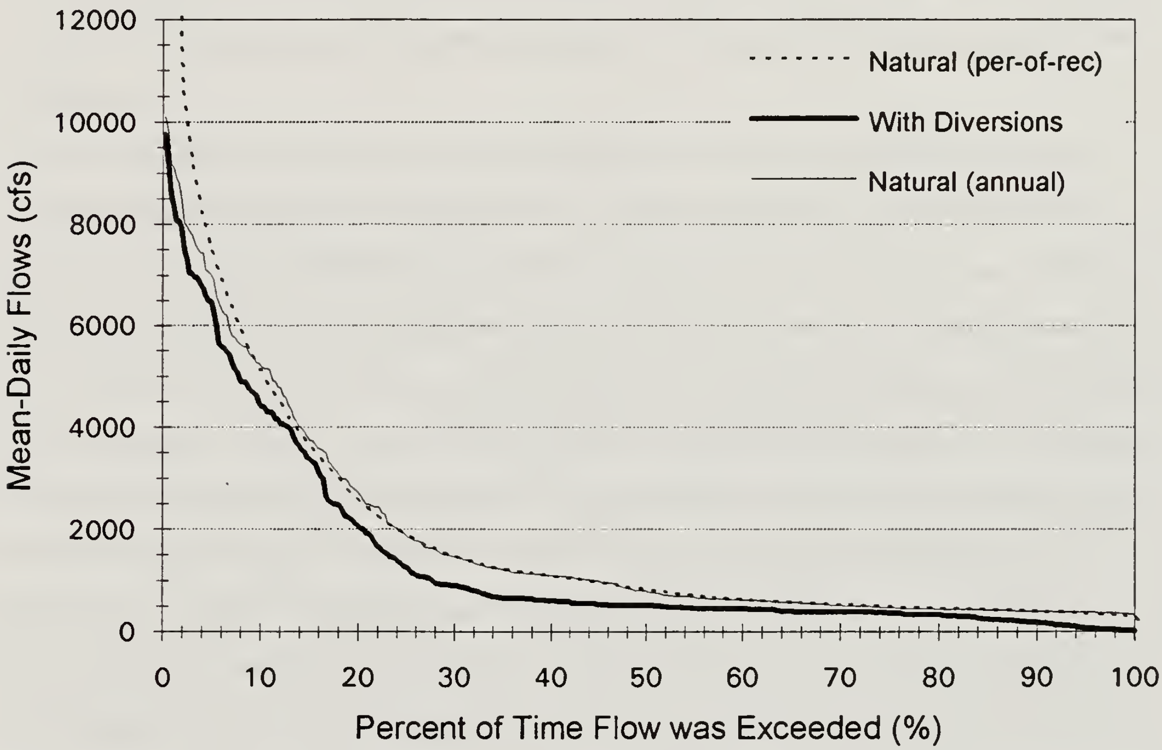

Fig.18 Flow-Duration Curves at BLCA, With and Without Diversions

Comparing the FDC's upstream and downstream from the tunnel indicates that the percent of time in which any given flow rate was exceeded has been reduced by the tunnel diversions for the whole range of flows, but predominately for the low-flows. This is shown graphically by the two curves not crossing each other, though they remain further apart for low-flows than what they do for high-flows. We can also observe in Figure 18 that the average mean-daily flow for the natural series (1,753 cfs) was exceeded only 26 percent of the time over the period of record. This indicates how positively skewed the series of daily flows really is.

b. *n*-Day Low-Flows Frequency

In addition to the FDA presented above, the magnitude and frequency of daily flows can also be evaluated by constructing time series of high- and low-flows variables for various time intervals, for instance: 1-day, 3-days, 7-days, etc, overlapping sub-sequences from the complete series of daily flows. Depending on the purpose of the investigation at hand, either high or low-flow variables and different *n*-days intervals may be of interest. Since low-flows is the most affected flow component for Scenario I, the *n*-day frequency analysis presented herein will focus exclusively on low-flows variables.

The computational procedure is based on the series of historic mean-daily flows. Overlapping sub-sequences of the selected low-flow variable are generated and the lowest flow for each water-year is selected. This procedure provides a new random variable representing the average discharge for the *n*-day interval. The distribution of the low-flow time series can be approximated by the empirical frequency distribution of the sequence, which in turn, can be fitted by a probability distribution if necessary. This empirical approach circumvents to a large degree the difficulties encountered in the theoretical analysis of low-flow variables, due to their large dependence and periodicity. Figure 19 displays two sets of curves for low-flows in the Gunnison River, upstream and downstream from the tunnel respectively. Each set contains *n*-day frequency curves for five durations, 1, 3, 7, 14 and 30-days. The vertical axis gives the average flow for the *n*-day time interval and the horizontal axis indicates the corresponding frequency in terms of the recurrence interval. Note for instance that the frequency curve for the 1-day interval is built with the same series of minimum-annual flows plotted in Figure 13.

The set of *n*-day curves for the "without tunnel" case lays well above the set for the "with tunnel" case in Figure 19. This indicates that tunnel diversions have caused a significant reduction in the *n*-day low-flow for all recurrence intervals. As an example, the average 14-day low-flow through the canyon having a recurrence interval of 2-years without any tunnel diversions would have been 370 cfs. However, diversions through the tunnel reduced this value to only 47 cfs

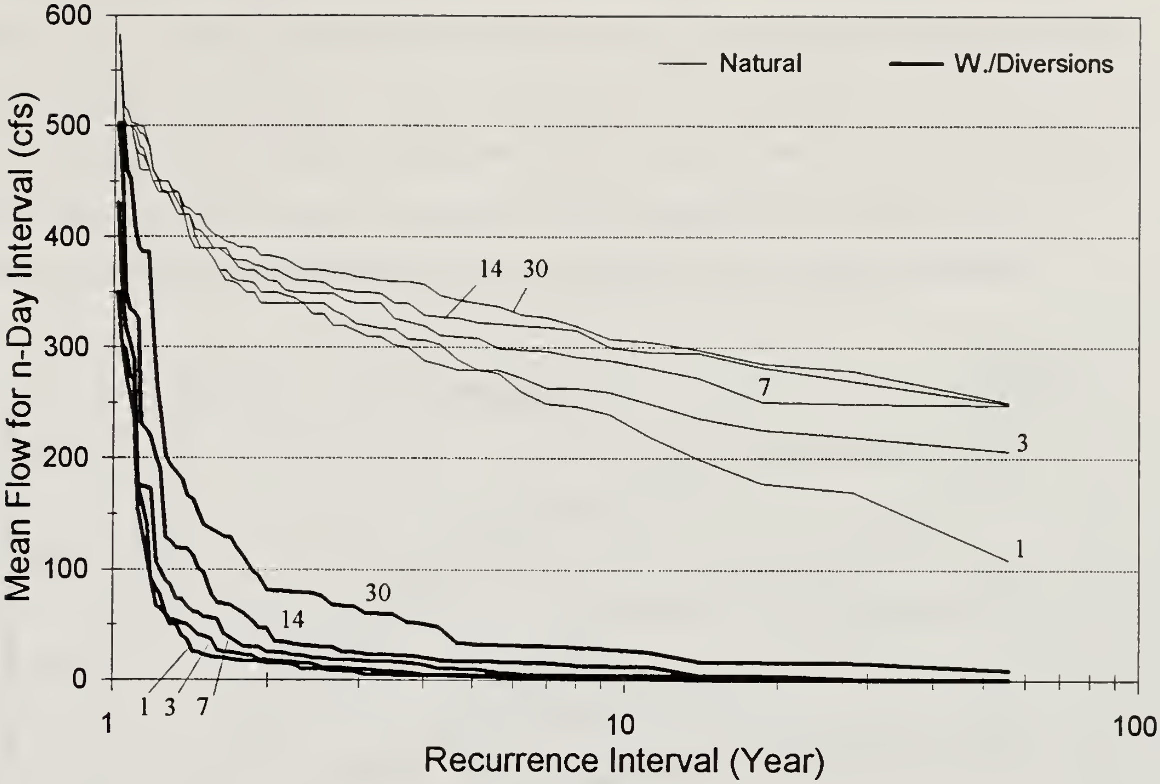

Fig.19 Frequency Curves for n-Days Low-Flows, With and Without Diversions

c. Low-Flows Crossing Levels

Crossing level analysis is performed by defining a threshold flow above or below which flow values are considered for the analysis. For high-flows crossing level analysis, the duration, or total number of days in which flows exceed the selected threshold is determined for each water-year. Using an empirical frequency distribution, the number of days in each water-year are then ordered and return periods are calculated. Similar analysis can also be performed using the total volume of water in excess of the threshold, so that the relative frequency of these events crossing the threshold level can be determined. For low-flow crossing levels the methodology is exactly the same except that the series of flows under analysis is made up of flow events that pass below the threshold value instead of above.

Only low-flow crossing level analysis was performed for the Gunnison River daily flows both upstream and downstream from the tunnel using total duration as well as

total volume below several threshold levels. Based on the annual series of minimum flows shown in Figure 13, the crossing levels chosen for this analysis include 100 cfs, 200 cfs, 300 cfs and 400 cfs. Figure 20 illustrates the relationship between total number of days below each crossing level and recurrence interval both upstream and downstream from the tunnel. A logarithmic scale was used in this figure for the return period axis so that points on the curve would be more evenly distributed.

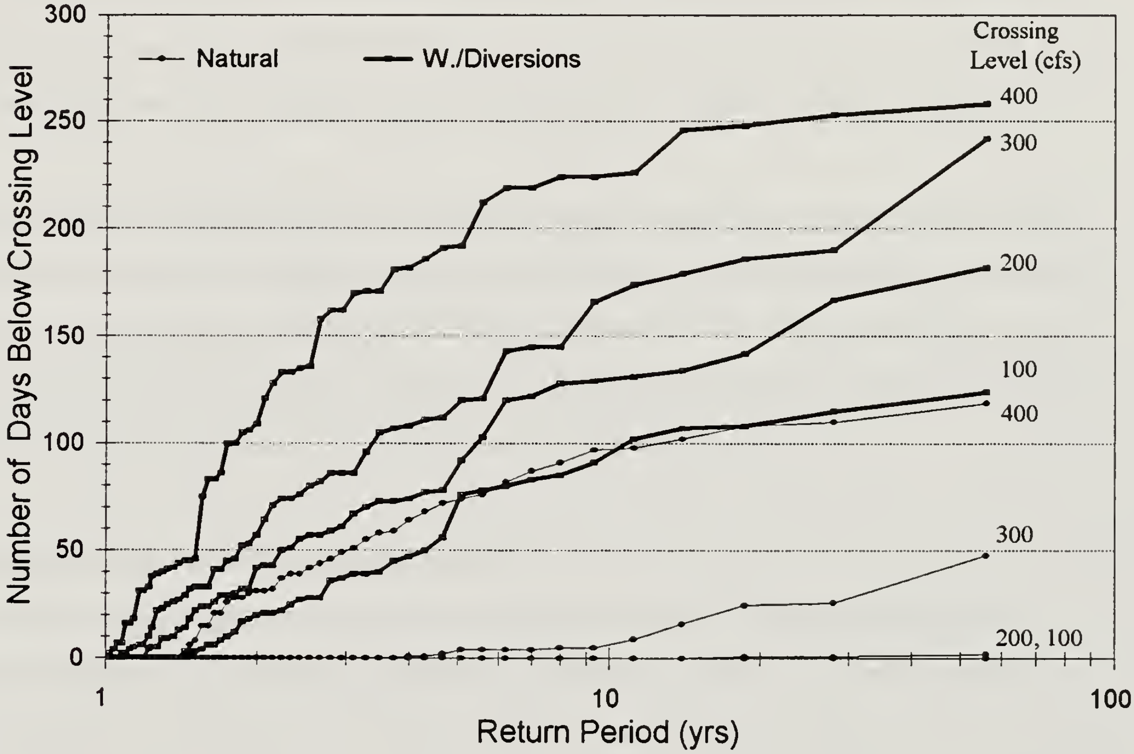

Fig.20 Duration of Low-Flows (Crossing Levels), With and Without Diversions

It is obvious from Figure 20 that tunnel diversions have increased the total number of days in which flow through the BLCA went below each of the four thresholds. Note for instance that the frequency of low-flows below the 400 cfs threshold upstream from the tunnel is roughly equivalent to the 100 cfs frequency curve after the tunnel. In other words, the number of days per year we would expect the Gunnison River to flow below 400 cfs in natural conditions is about the same number of times the flow actually crosses below 100 cfs with after tunnel diversions take place (for all recurrence intervals). The results displayed in Figure 20 can also be interpreted as

follows: for a given return period, let's say 10 years, natural flows went below 300 cfs only 6 times (on average 6 times in 10 years). But because of tunnel diversions, we should expect flows to drop below 300 cfs an average of 170 times in the same 10 years period. Results similar to those described above were also found for the analysis of total volume or deficits below each crossing level (not shown). High-flow crossing level analysis was also carried out using three different threshold values, including 10,000 cfs, 12,500 cfs and 15,000 cfs. While tunnel diversions caused a slight decrease in the total duration as well as total volume of water exceeding these thresholds, the differences were not as significant as in the low-flow analysis.

We should remind the reader that all frequency analysis presented in this section are based on the period of record 1911-1965. Since the present level of tunnel diversion is roughly a 32% larger than the average that corresponds for the period 1911-1965 (see Figure 9), we expect the adverse impact of tunnel diversions in the minimum flows at Black Canyon to be even more accentuated than what has been shown in this study.

3.5 Seasonal Impact of Tunnel Diversions

Dividing each water-year into two main seasons help us further understand the hydrological impact of the Gunnison Tunnel in the BLCA. Water is diverted through the tunnel during nearly 70 percent of the year, hence, it was decided to split the water-year into the *irrigation* and *non-irrigation* seasons. After examination of tunnel flows records, the irrigation season was chosen to begin on March 16th and end on November 27th, lasting a total of 257 days. The non-irrigation season, in which little or no diversions through the tunnel occur, lasts from November 28th until March 15th of the following calendar year, for a total of 108 days. The non-irrigation season then represents the period of the year in which the difference between flow upstream and downstream from the tunnel was three percent or less, see Figure 9. The seasonal analysis was performed using the mean-daily flows within each season rather than for the entire water-year. Even though these seasons do not have equal lengths, their analysis does shed additional information on the effects of the tunnel diversions.

The average mean-daily flow over the entire period of record for each season was computed upstream and downstream from the tunnel. For the non-irrigation season, the mean- daily flow upstream and downstream from the tunnel was nearly identical since very few diversions through the tunnel occur during this season. During the irrigation season when most of the diversions occur, though, the tunnel causes the average of the mean-daily flow through the Black Canyon to be reduced from 156.5 cfs to 104 cfs. This amounts to a reduction in average flows by roughly one-third over the irrigation season.

Separate flow-duration analysis were computed for each season using all of the mean-daily flows over the 55 year study period for each respective season. Because the irrigation season overlaps two successive water-years, the period-of-record method was used rather than the annual flow-duration approach previously described. As would be expected, the flow-duration curves for the non-irrigation season upstream and downstream from the tunnel were nearly identical. For the irrigation season, tunnel diversions caused the percent of time that a given flow was exceeded to be reduced. The same conclusion was drawn from the daily flow- duration curves for the entire water-year, but the differences are more dramatic during the irrigation season alone. For example, using a flow rate of 542 cfs, this flow would have been exceeded 90 percent of the time during the irrigation season if no diversions through the tunnel had been made. Because of tunnel diversions, this same flow rate was exceeded only 59 percent of the time, a difference of 31 percent.

4.0 HYDROLOGICAL IMPACT OF THE ASPINALL RESERVOIRS

Scenario II analyses changes in flow conditions in the BLCA caused by flow regulation in the Aspinall Units. As described in Section 2.3 of this report, flows upstream from the Gunnison Tunnel between water-years 1911 to 1965 were compared with flows at the same location between water-years 1971 to 1993. The first time series ends before any of the reservoirs were operated, considered then undisturbed, while the second time series begins after operation of the two largest reservoirs had begun. Although the third reservoir (Crystal) did not start operation until 1977, is not expected to significantly change the results of this analysis given its small storage capacity.

A measure of the regulation capacity of a reservoir is given by the ratio of its storage capacity versus the mean annual inflow. The computations show values of 66%, 4.1% and 1.6%, for Blue Mesa, Morrow Point and Crystal respectively. These figures indicate the predominance of Blue Mesa over the other two reservoirs to regulate flows in a seasonal basis, whereas Morrow Point and Crystal have the capability to regulate flows only at the weekly and daily level respectively. Moreover, since reservoirs regulate flows in such a way that the periodicity of the flow series is practically removed, scenario II does not include any hydrological analysis at the seasonal level. It should be noted that the USBR has made several attempts to operate the Aspinall Units simulating near-pre-dam flow conditions. This periodic changes in operation are embedded in the time series that we are analyzing. The study of the modifications in the reservoir operational rules is beyond the scope of this study.

4.1 Impact of Flow Regulation on the Series of Annual Flows

The time series of annual volumes in the Gunnison River both pre- and post-impoundment are plotted in Figure 21. Recall that at this location in the river, upstream from the Gunnison Tunnel, the change in the annual volumes does not include the effects caused by tunnel diversions. As Figure 21 indicates, the annual volumes were slightly reduced after the reservoirs began operation, from 1,269,363 ac-ft to 1,213,965 ac-ft, a 4.4 percent. As with the analysis in the previous chapter, several statistical and graphical tests were performed, including the Mann-Whitney test, the S-S plot and the double mass curve,

all of which confirm that this is not a statistically significant change. Average levels of annual volumes for the first series before and after changes in the Gunnison Basin around 1930 are also indicated in Figure 21, with a clear shift in 1930. The subsequent small increase in the average level of annual volumes after 1971 can be attributed to sampling variability.

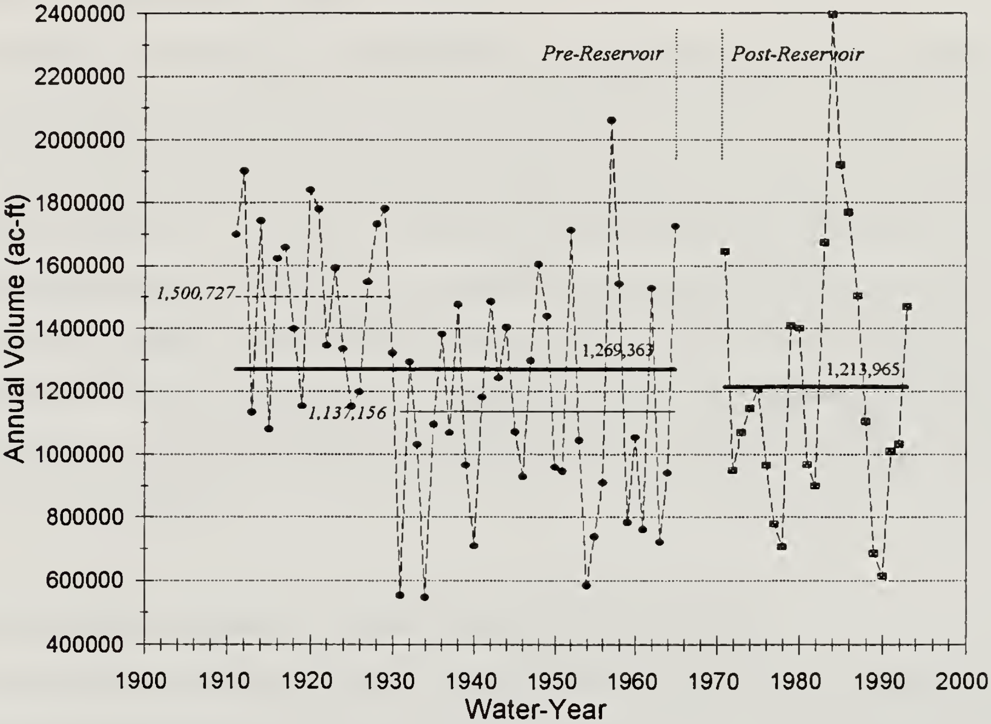

Fig.21 Annual Flows at BLCA, Pre- and Post-Regulation

Because the two annual series of volumes represent two different time periods, precipitation records were also examined to determine if any changes in precipitation occurred after the reservoirs began operation. Of the three precipitation gages described in Section 2.6, two gages indicated a slight increase in precipitation of between one to three percent for the water-years 1911 to 1965 and 1971 to 1993. The third gage, located at the City of Gunnison, experienced a significant decrease in precipitation of roughly 15 percent over the same time periods. Since these results are not consistent, no definite conclusion could be reached about changes in precipitation causing changes in flows through the Black Canyon over these two periods.

A brief analysis was also made to determine if evaporation losses from the Aspinall Reservoirs may have had a significant effect on annual volumes in the BLCA. Using evaporation data provided by the U.S. Bureau of Reclamation, evaporation losses from the three reservoirs were found to be negligible compared to the annual flow volumes, only a 0.7 percent. Hence, the slight reduction in annual volumes after the reservoirs were constructed is attributed to a combination of these two factors.

In addition to the mean of the sub-periods, the standard deviation of the annual volumes was also determined before and after the Aspinall Reservoirs were built. The annual volumes in the river after the reservoirs were in place was found to have an increase in the standard deviation of 17 percent. The relatively short length of the series for the post-impoundment period case is more likely to introduce larger sampling variability than the longer first series. Finally, the quantiles for these annual volumes were calculated for each time series before and after the reservoirs. In general, the curve representing volumes after reservoir regulation was slightly lower than the curve before reservoir regulation, though the two curves were very close.

4.2 Impact of Flow Regulation on the Series of Extreme Flows

The annual series of extreme flows were extracted from the series of mean-daily flows, and are composed by the maximum and the minimum values registered on each water-year.

4.2.1 Annual Maximum Flows

The series of maximum flows, before and after the reservoirs (regulation), are plotted in Figure 22. Unlike the effect of the Gunnison Tunnel, the Aspinall Reservoirs significantly alter the series of peak flows. As Figure 22 indicates, the mean of this series was reduced from 9,553 cfs to 3,957 cfs, representing a reduction of almost 60 percent. Statistical tests confirmed the fairly obvious downward shift between the two subsamples. This drastic decrease in annual-maximum flows is a direct consequence of the large capacity of the three Aspinall Units operating in series to regulate flows in the Gunnison River.

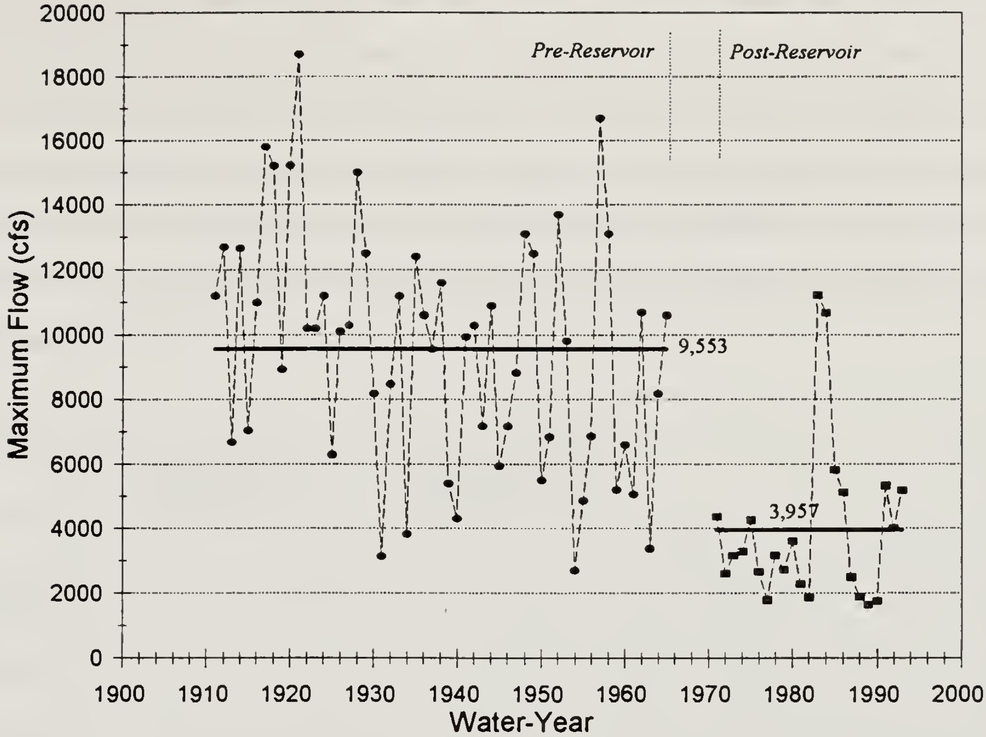

Fig.22 Annual Maximum Flows at BLCA, Pre- and Post-Regulation

4.2.2 Annual Minimum Flows

The series of annual-minimum flows was also compared before and after the Aspinall Reservoirs entered operation. The average of the series was found to increase from 349.8 cfs to 369.2 cfs after 1971. This upward shift by 5.5 percent was also tested but determined to not be statistically significant.

4.3 Impact of Flow Regulation on the Series of Daily Flows

Similar analysis to the one performed on the daily time series to determine the effect of the Gunnison Tunnel were also performed to study the effect of the Aspinall Reservoirs. The methods used for each analysis will not be repeated again, so the interested reader should refer to the appropriate sections in Chapter 3.

4.3.1 Basic Statistics of the Mean-Daily Flows

Initially, the mean-daily flows for each day of the water-year were determined for the two time series before and after regulation by the reservoirs began. As shown in Figure 23,

though the mean of the series after the reservoirs is only slightly lower than before (a 4.4% difference between pre- and post-impoundment), regulation by the reservoirs has totally changed the shape of the mean-annual hydrograph. Mean-daily flows are significantly higher outside the snowmelt season due to the regulation effect of the reservoirs, and the typical peak in runoff during the spring and early summer has been eliminated. In other words, the Aspinall Reservoirs are responsible for suppressing much of the seasonal variations in flow through the Black Canyon.

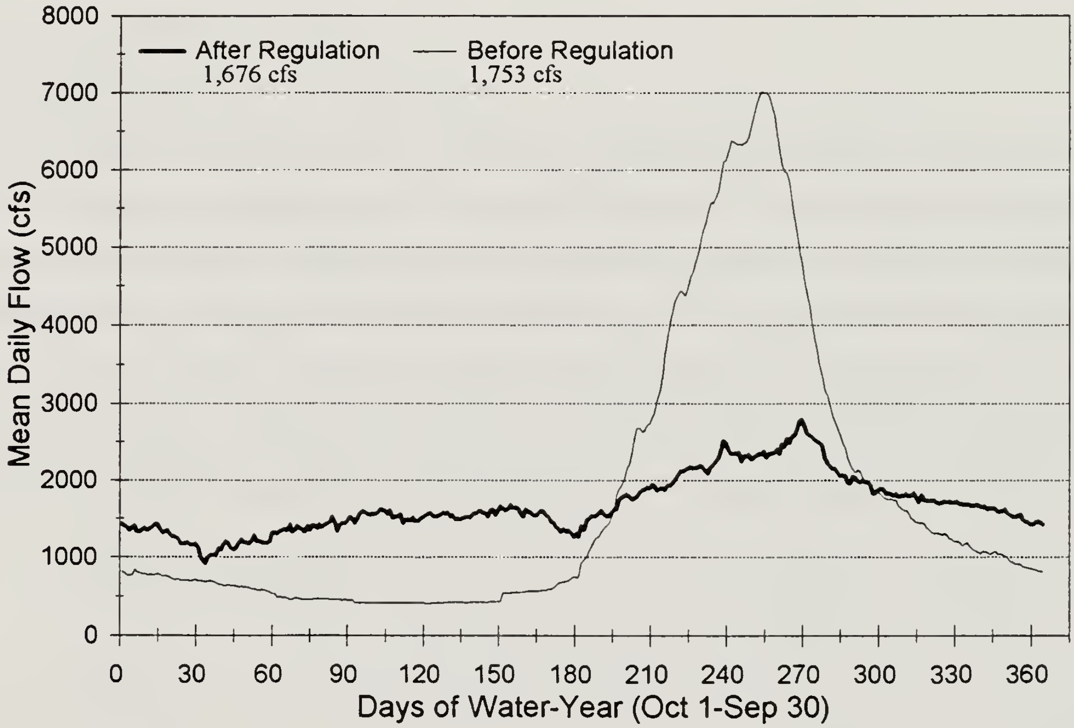

Fig.23 Daily Mean Flows at BLCA, Pre- and Post-Regulation

In addition, although Figure 23 is constructed using mean flows for each day of the water-year, it also gives an indication of the possible reduction in the range of daily flows caused by reservoir regulation. The range is defined here as the difference between the maximum and minimum flows for the entire time series. The actual range in daily flows at BLCA was reduced by the reservoirs from roughly 18,590 cfs to only 11,190 cfs

While the average of the mean daily flows was decreased a 4.4 percent, the standard deviation was actually increased by roughly 4 percent. Most of this increase occurs during

the first half of the water-year when there is naturally much less runoff in the basin. During the second half of the water-year when snowmelt generates most of the runoff, the deviation in flows has generally been reduced by the reservoirs. Finally, the auto-correlation coefficient was determined for each day of the water-year as a measure of the correlation between flows in two successive days. Because the natural runoff mostly consists of highly correlated flows from snowmelt, the reservoirs introduce practically no change in the correlation of daily flows. The periodic auto-correlation coefficient is maintained very uniform for the entire water-year, being reduced from 0.95 to 0.92 due to the presence of the reservoirs, an insignificant change.

4.3.2 Marginal Distributions of Daily Flows

The marginal distribution of the mean-daily flows through the Black Canyon was drastically changed by regulation from the Aspinall Reservoirs. The marginal distribution for the time series upstream from the tunnel was previously plotted in Figure 16 and appears very indicative of an unregulated, snowmelt driven basin. The marginal distribution that results due to the reservoirs is shown in Figure 24 and appears very characteristic of a highly regulated flow regime. Once again, only the curve that represents the 95% nonexceedance probability (very high flows) shows any resemblance to the seasonal pattern of natural flows.

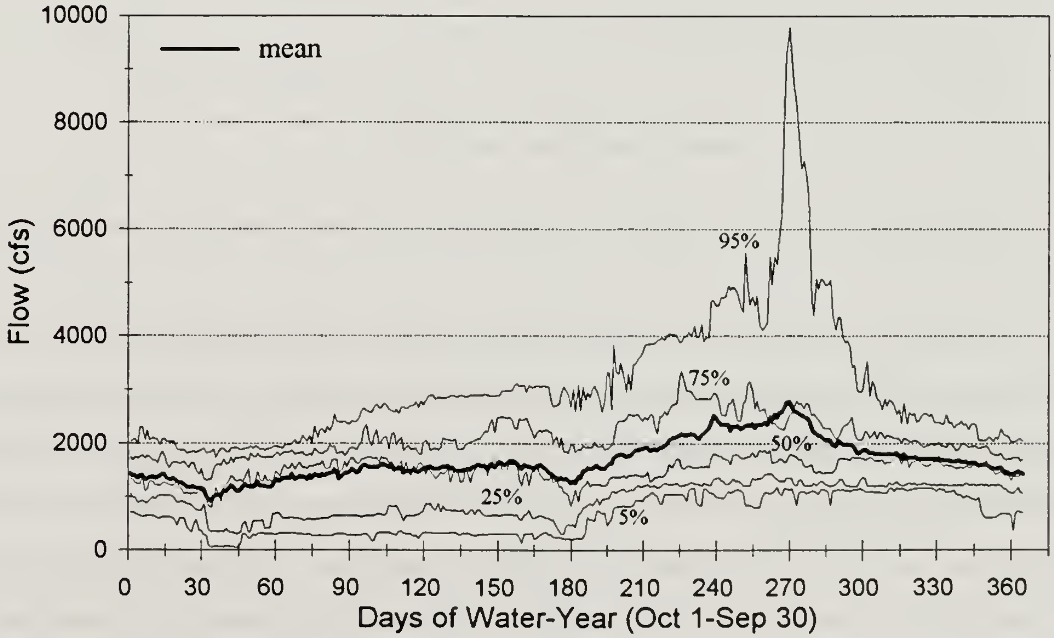

Fig.24 Marginal Distribution of Daily Flows at BLCA, Post-Regulation

4.3.3 Magnitude and Frequency of Daily Flows

a. Flow-Duration Analysis

Once again, flow-duration curves were computed for the pre- and post-impoundment scenarios using the traditional period-of-record FDA and the median-annual FDC method. Because the annual flow-duration curve is more likely to represent long term processes, the results from the latter procedure are discussed here. Figure 25 shows median-annual flow-duration curves before and after the reservoirs started operation.

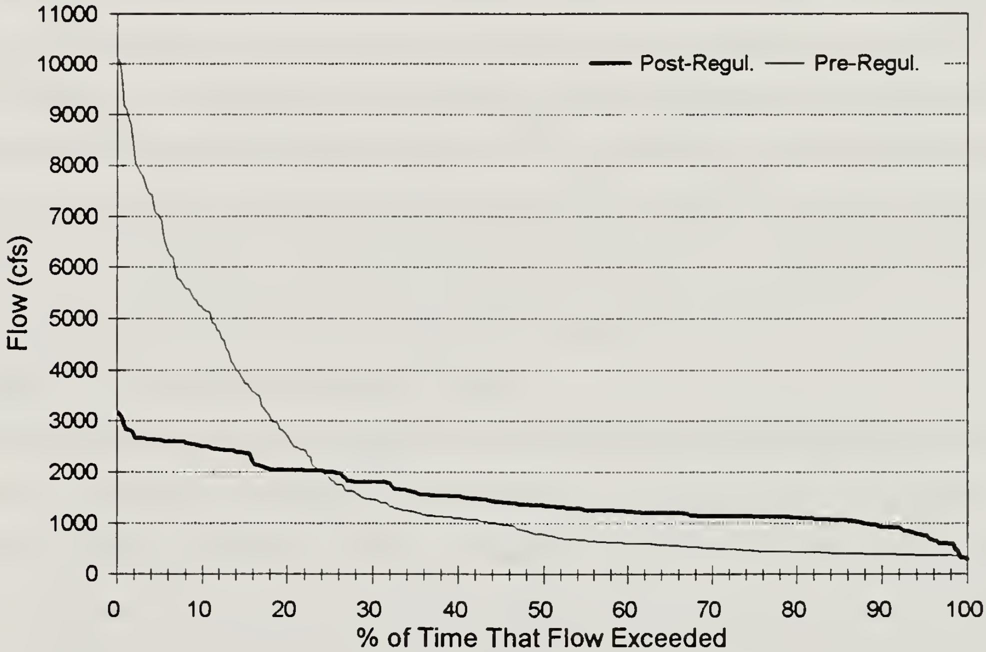

Fig.25 Flow-Duration Curves for a "Typical" Water-Year, Pre- and Post-Regulation

The FDC for regulated flows is much flatter than the curve before regulation, indicating a drastic reduction in the range of daily flows caused by the reservoirs. In addition, the fact that the two curves in Figure 25 cross each other indicates that reservoir regulation has caused high flows to be exceeded a lower percentage of the time and low flows to be exceeded a higher percentage of the time than under natural conditions. For instance, in a median or "typical" water-year before regulation, a flow level of 6,000 cfs would be exceeded 6.7 percent of the time (approximately 25

days per year), whereas for a "typical" water-year after regulation this flow level would never be reached. Recall that these values represent probabilities for a median water-year, since actually 6,000 cfs was exceeded once during the 23 year period of record after the reservoirs were built. In contrast to the effect on high-flows, the reservoirs have dramatically extended the duration of low-flows. For example, flows around 800 cfs have practically doubled the percent of time in which they can be exceeded, from 50 percent to 95 percent.

b. *n*-Day High-Flows Frequency

Consistent with the analysis of the Gunnison Tunnel, the daily flow frequency analysis was also performed for both high- and low-flows using the same intervals of 1, 3, 7, 14, 30-days, etc. In general, the reservoirs caused a reduction in the mean *n*-day high-flow for each of the above intervals. As an example, the highest mean 30-day flow for an average 2-year period was reduced from 6,936 cfs to just 2,479 cfs by the reservoirs. On the other hand, the mean *n*-day low-flow was increased for all intervals but mainly for the lower recurrence intervals.

c. High- and Low-Flows Crossing Levels

As before, the crossing level analysis was carried out for both high-flows and low-flows by measuring both duration and volume. For the high-flows, the same threshold values were used as before, including 10,000 cfs, 12,500 cfs and 15,000 cfs. In general, the reservoirs caused a significant decrease in the number of times each threshold was exceeded, as well as the total volume of water above each threshold. For example, the total number of days in which flows would exceed 10,000 cfs during an average eight year period before the reservoirs began operation was 15. Once the reservoirs started regulating flows this threshold would not be exceeded at all during an average eight year period. Figure 26, graphs a and b, illustrate this dramatic change in the duration of high-flows caused by the reservoirs.

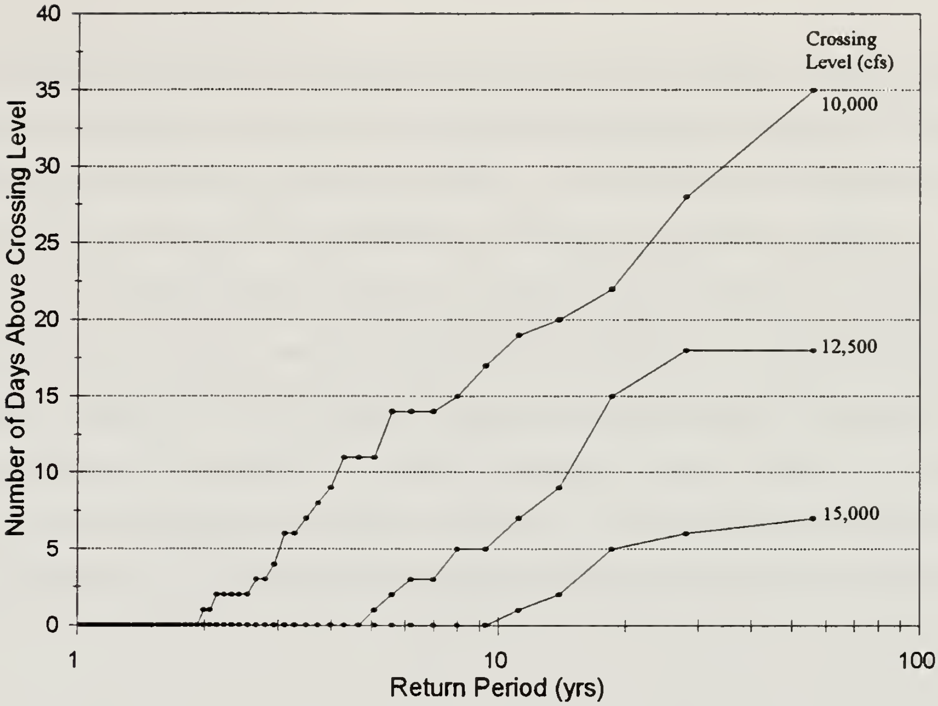

Fig.26a Duration of High-Flows at BLCA, Pre-Regulation

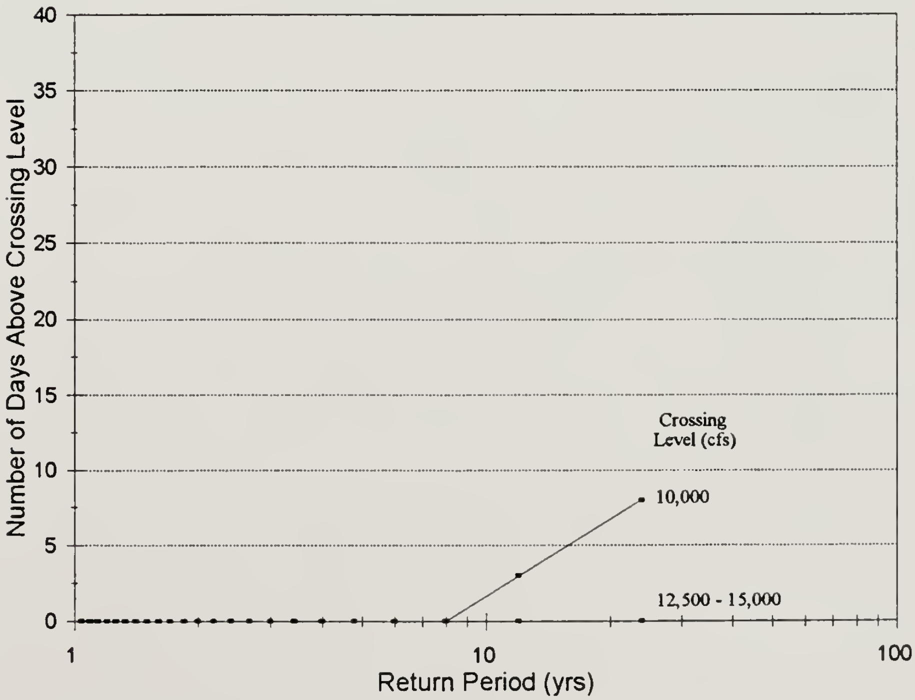

Fig.26b Duration of High-Flows at BLCA, Post-Regulation

When repeating the threshold analysis but this time for low-flows, it was found that as expected the presence of the reservoirs noticeably decreased the number of times in which flows crossed below a specific threshold. This typical flow augmentation effect produced by the reservoirs was observed for threshold levels above 350 cfs. However, for thresholds below 350 cfs (the lowest flows), practically no difference was found between the pre- and post-impoundment scenarios. Although undetectable at the scale of Figure 25, this finding could have been anticipated from the flow-duration analysis. The two FDC's shown in that graph cross each other for a second time at a percent exceedence very close to 100%. This tends to distort results from the *n*-day frequency and crossing level analysis for the very low flows, less than 350 cfs.

5.0 COMBINED HYDROLOGICAL IMPACT OF TUNNEL AND RESERVOIRS

The hydrological analysis described in Scenario III combines the effects of the Gunnison Tunnel and the Aspinall Reservoirs on the streamflow regime through the BLCA. As indicated in Section 2.4 of this report, two flow series are used for the analysis. The first series was chosen upstream from the tunnel and before the reservoirs so that neither of these structures had any influence on flows through the Black Canyon. The second series was chosen at the site downstream from the tunnel and after the reservoirs so that the effect of both structures is incorporated. Since scenario III includes the effect of flow regulation, the hydrological analysis of flows at the seasonal level was deemed unnecessary.

5.1 Tunnel and Reservoirs Impact on the Series of Annual Flows

The time series of annual volumes in the Gunnison River both with and without the combined effects of the tunnel and the reservoirs are plotted in Figure 27. The combined effect of the tunnel and reservoirs caused a reduction of the annual volumes in the river by 30.2 percent if the average for the period 1911-1965 is used as baseline for the computations, or 22.1% if the average for the sub-period 1931-1965 is considered instead. Again, because the two series represent different time periods, other factors such as a reduction in annual precipitation may have partially contributed to this shift. Using the same tests previously mentioned, this downward shift was confirmed to be statistically significant. It is also known form the previous analysis of Scenario I (Figure 11) and Scenario II (Figure 21) that the reservoirs cause practically no change in the series of annual flows, therefore the change observed for Scenario III is practically entirely due to the tunnel diversions.

Same as for Scenarios I and II, the standard deviation of these annual volumes was also determined for each of the two series. The series of annual volumes which includes the combined effect was found to have a higher deviation in annual volumes by a factor of 23.4 percent. In addition, the quantiles for each series of annual volumes were calculated. The curve representing the effects of the tunnel and reservoirs lies below the curve for natural flow conditions, very similar to those shown in Figure 12. This means that for all return

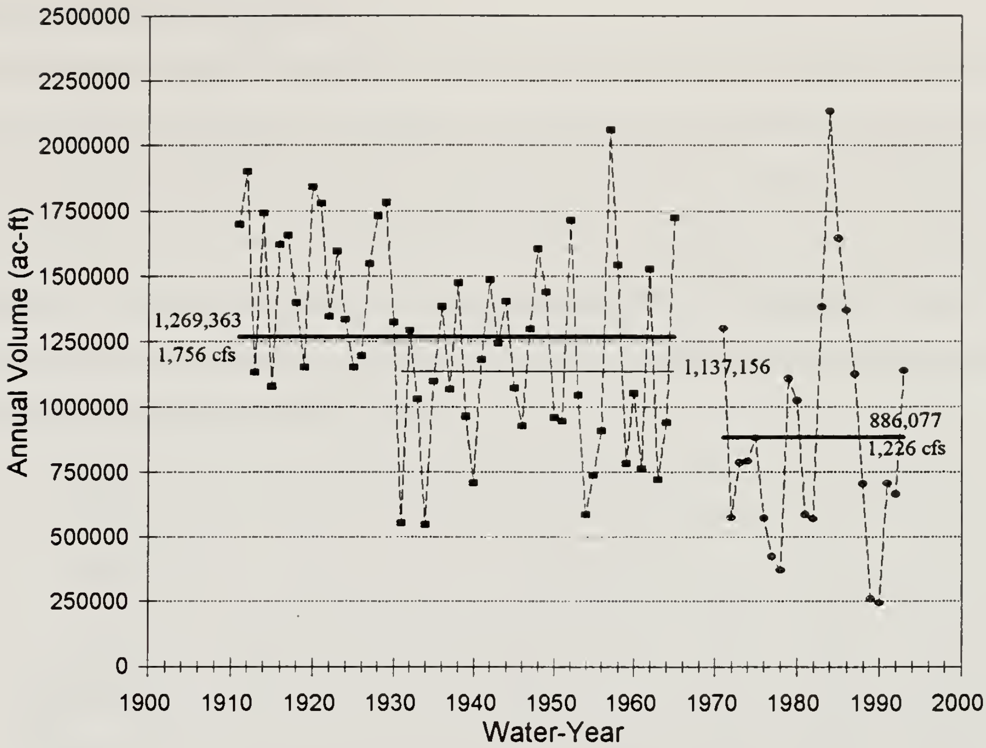

Fig.27 Annual Volumes at BLCA, With and Without Structures

periods, the operation of the tunnel and reservoirs reduce the annual volume of water in the Gunnison River. To illustrate, the annual volume associated with a 2-year return period under natural conditions was reduced from 10,000 acre-feet to only 2,740 acre-feet due to both the presence of the tunnel and the reservoirs.

5.1.1 Annual Maximum Flows

The series of annual-maximum flows were determined for each of the time series and found to be very similar to the maximum flows plotted in Figure 22 for Scenario II. The same baseline condition was used, between 1911 to 1965, so only the second series was slightly altered. The same pattern of maximum flows was observed, except that the mean of the maximum flows for the second series was further reduced from 3,957 cfs for Scenario II to 3,552 cfs for the combined action of the reservoirs and the tunnel. In other words, the mean of the annual-maximum flows was further decreased from 41.4 percent to only 37.2 percent of the average annual-maximum flows under natural conditions. Though evident, this downward shift was tested and confirmed to be statistically significant.

5.1.2 Annual Minimum Flows

The series of annual-minimum flows for each time series are plotted in Figure 28. In this case, the combined effect of the tunnel and reservoirs was found to reduce the mean value of the annual-minimum flows from 349.8 cfs to 255.0 cfs. This represents a downward shift of 27.1 percent and is also statistically significant. In fact, the downward shift would have been even more evident (near 35 percent) had it not been for the irregularly large minimum flow registered during water-year 1986, which increases the average minimum-flow for the period 1965-1993.

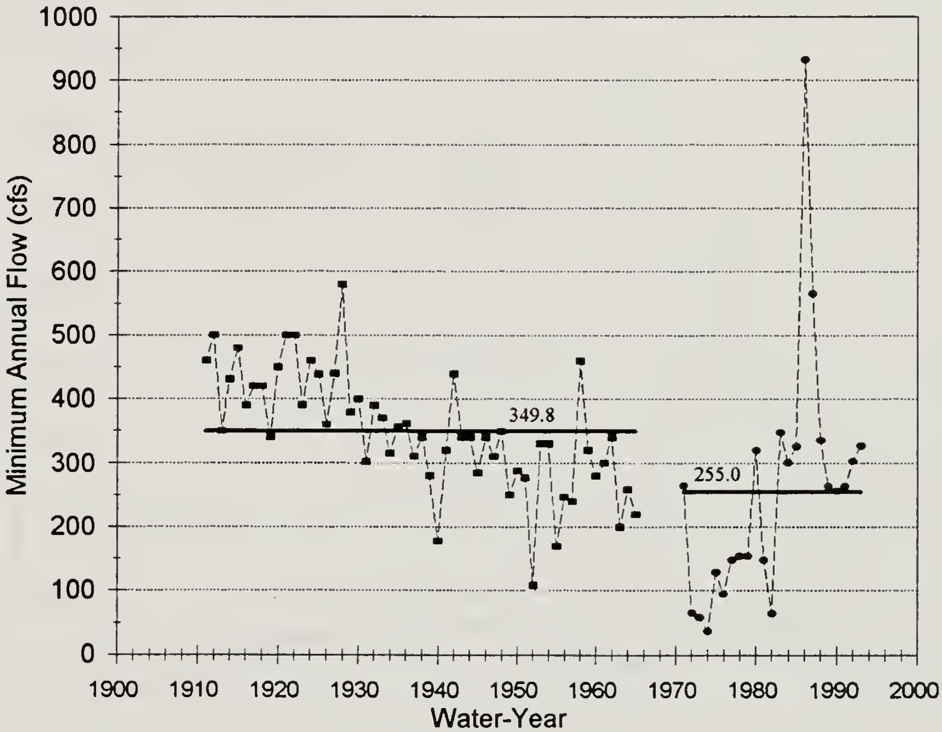

Fig.28 Annual-Minimum Flows at BLCA, With and Without Structures

Minimum flows constitute a clear example of how the combined effect of tunnel diversions and flow regulation sometimes tends to conceal the dramatic adverse effect that just one of the structures may have on a specific streamflow characteristic. While water diversions through the tunnel alone drastically reduces the average minimum flow from 349.8 cfs to an average of 15 cfs (see Figure 15), the combined effect of both structures operating simultaneously bring the average minimum flow back up to a level of 255 cfs.

5.2 Tunnel and Reservoirs Impact on the Series of Mean-Daily Flows

5.2.1 Basic Statistics of the Mean-Daily Flows

The mean-daily flows for each day of the water-year were calculated for both series and plotted in Figure 29. The series which represents existing or present conditions not only has a lower average of the mean-daily flows but also a much flatter curve, indicating that nearly all the natural seasonal changes of the flow regime have been eliminated by the operation of the tunnel and reservoirs. Whereas the reservoirs produce a dramatic change in the shape of the mean-annual hydrograph, the tunnel diversions drastically reduce the total volume of the hydrograph. Essentially, not a single element of the mean-annual hydrograph has remained unchanged.

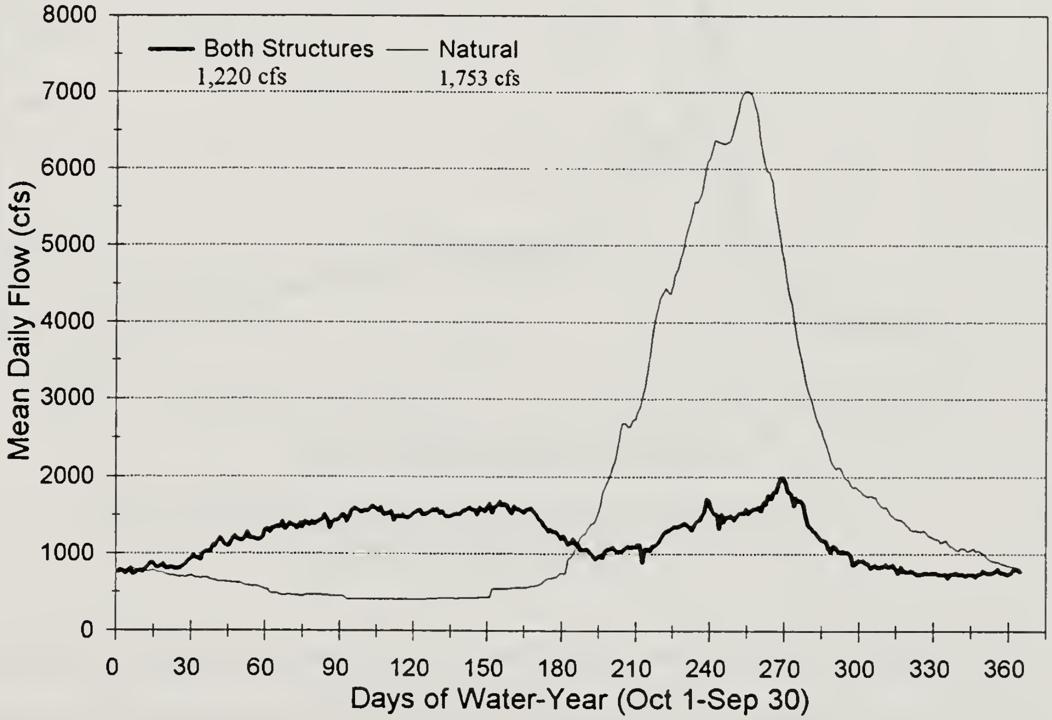

Fig.29 Daily-Mean Flows at BLCA, With and Without Structures

The actual range between the highest and lowest flows over each period of analysis was reduced from 18,590 cfs to just 10,600 cfs by the tunnel and reservoirs, a slightly greater reduction than in the case of the reservoirs only. Once again, the average standard deviation of these mean-daily flows was increased by the presence of both structures from

840.4 cfs to 914.3 cfs. The periodic changes in the standard deviation for both conditions, with and without the structures, are shown in Figure 30. Diversions and flow regulation introduce an increase in the variability of mean-daily flows during the first half of the water-year and a decrease during the snowmelt season. However, when flow variability is expressed in terms of the relative amount of flow, denoted as Cv, it was found that the coefficient of variation uniformly increases for practically all days of the water-year when compared with natural conditions.

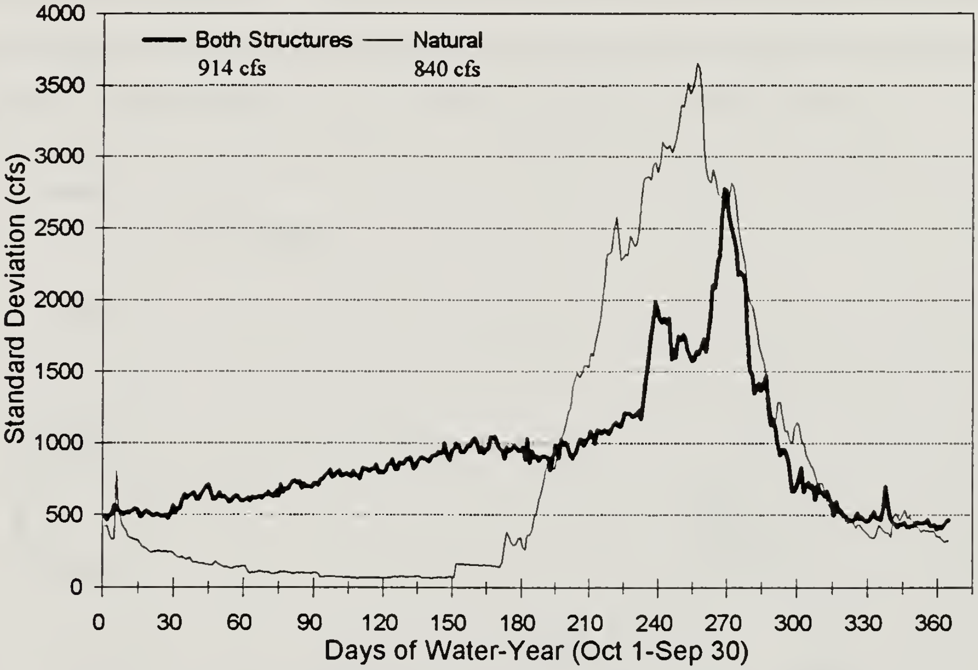

Fig.30 Periodic Standard Deviation of Daily Flows at BLCA, With and Without Structures

In addition, the periodic autocorrelation coefficient with lag-1 was found to have a uniformly high value throughout the water-year for both series, only slightly reduced from 0.95 to a value of 0.92 for the combined effect of tunnel and reservoirs.

5.2.2 Marginal Distributions of Daily Flows

The marginal distributions of mean-daily flows for near natural conditions was previously presented in Figure 16. The curves in Figure 16 represent typical flow distributions for a basin in which runoff is practically unregulated and predominately dominated by

snowmelt. The marginal distributions for the flow series with the combined effect of the tunnel and the reservoirs were plotted in Figure 31. Again, the operation of the tunnel and the reservoirs has significantly altered the natural distribution of the daily flows through the Black Canyon.

Although the most obvious changes can be perceived when comparing the natural conditions case (Figure 16) versus the scenario with only reservoirs in the system (Figure 24), the combined effect of the tunnel plus the reservoirs tends to further lower the distribution curves in Figure 31, especially for percentiles equal to and less than 50%. Only flows for the 95 percentile curve provide some indication of the highest flow peaks that should naturally reach the Black Canyon during the spring and early summer.

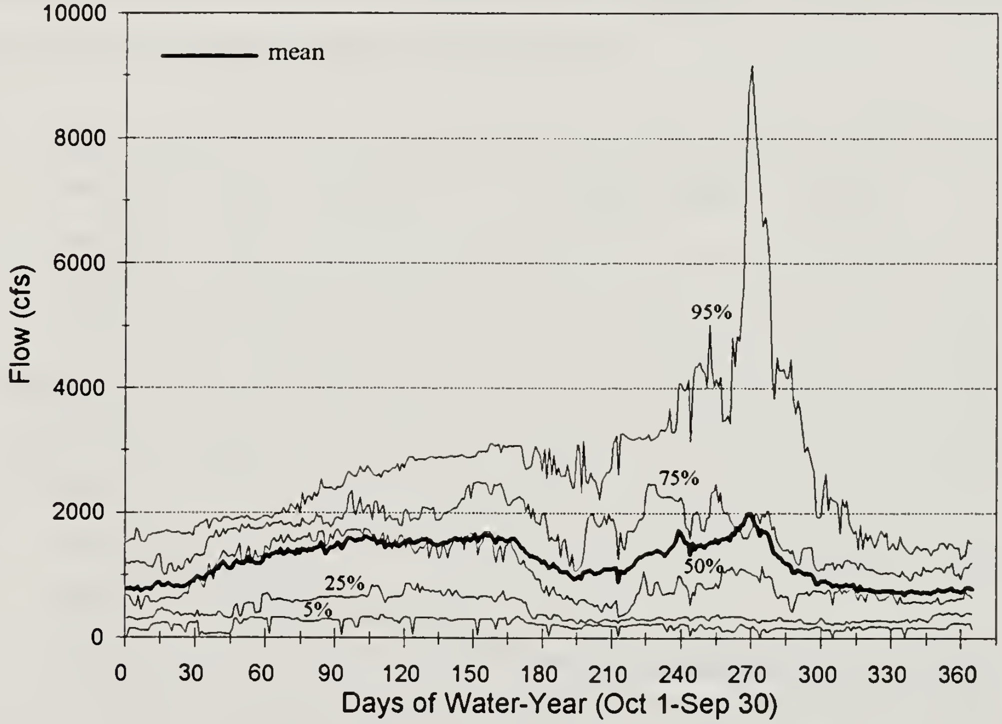

Fig.31 Marginal Distributions of Daily Flows at BLCA, With Structures

5.2.3 Magnitude and Frequency of Daily Flows

a. Flow-Duration Analysis

As for previous scenarios, flow-duration analysis was performed using both the period-of-record and the median-annual flow duration curve methods. The two curves

plotted in Figure 32 depict the median-annual flow-duration curves, representative of "typical" water-years under the two different conditions. Notice that these two curves are fairly similar for flows which are exceeded roughly 30 percent of the time or more but then diverge noticeably for larger flows. For these larger flows, therefore, the effect of the tunnel and the reservoirs operating simultaneously cause a significant decrease in the percent of time that any of these high-flows are exceeded. For example, the influence of the reservoirs and the tunnel cause the percent of time in which a flow of 2,000 cfs is exceeded to be reduced from 24.2 percent to 13.0 percent. Similarly, we can also deduce from Figure 31 that during a "typical" water-year, the largest peak flow expected to reach the Black Canyon area for the present conditions (with tunnel diversions and reservoir regulation) is only near 30 percent of what would be expected under natural conditions.

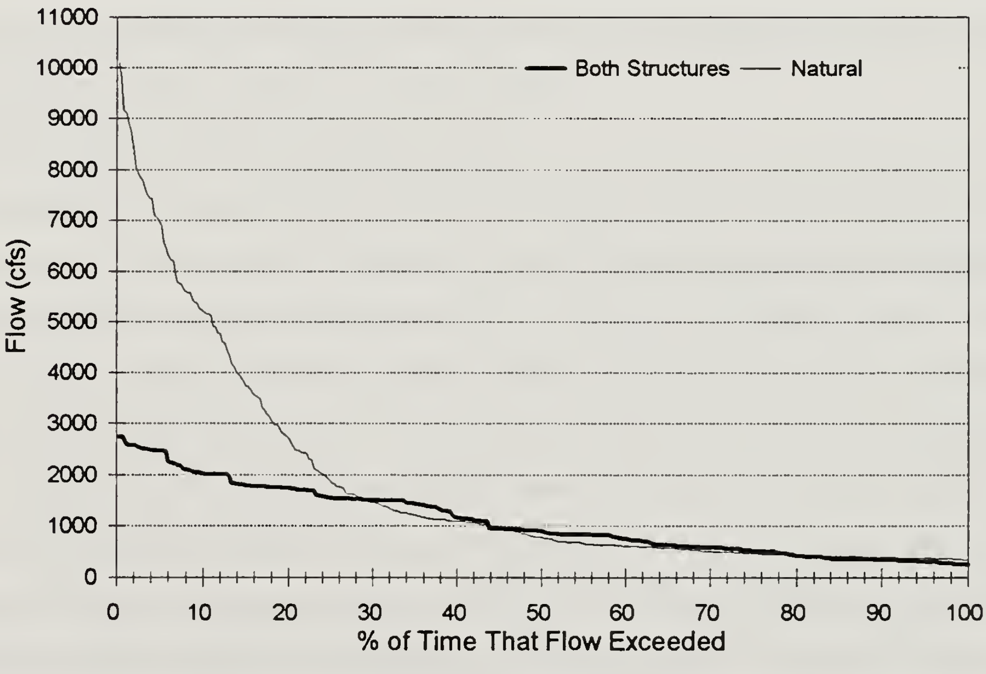

Fig.32 Flow-Duration Curves for a "Typical" Water-Year, With and Without Structures

The incremental adverse effect of tunnel diversions after flows are regulated by the reservoirs can also be readily detected by comparing the FDC under impacted

conditions from Figure 25 (after regulation) with the same curve in Figure 32 (after regulation and diversions). Note the general down-shifting of the dark curve for the whole range of flows, and in particular for flows with durations larger than 30 percent.

b. *n*-Day High- and Low-Flow Frequency

The combined effect on the *n*-day mean high-flows and *n*-day mean low-flows was determined for each series of daily flows. The results show that the mean *n*-day high-flows were decreased for each of the six time intervals analyzed (from 1- to 90-days) and for all return periods. Likewise, the combined influence of the tunnel and reservoirs affects the mean *n*-day low-flows in a manner similar to that shown in Figure 19, although the vertical distance between the two sets of curves is not as pronounced as in Figure 19. In fact, for the lowest recurrence intervals, from 1 to 2 years, the set of curves for altered conditions crosses the set of curves for natural conditions, reaching values above 500 cfs. This is a consequence of the low-flow augmentation effect introduced by the reservoirs.

c. High- and Low-Flows Crossing Levels

The combined impact of the operation of the tunnel and reservoirs has also been investigated by using both the high-flow and the low-flow crossing level analysis. For the high-flow analysis, both the duration and volume in excess of three selected high-flow thresholds (10,000, 12,500, 15,000 cfs) were dramatically reduced by the operation of the two structures. The results are similar to those shown in Figure 26b for the case of reservoirs only, except that when the impact of the tunnel and reservoirs is jointly analyzed, the curve for 10,000 cfs shown in Figure 26b has practically all its ordinates near zero, even for return periods larger than 8-years. For the low-flow analysis, the frequency of the total number of days with flows going below 100, 200, 300, and 400 cfs were investigated, and the results plotted in Figure 33. While the low-flow crossing-level analysis for Scenario I (only tunnel diversions) revealed a general increase in the number of days in which flows fall below each of the threshold levels analyzed (see Figure 20), the combined impact of the tunnel and reservoirs yielded more irregular results. Comparing Figures 33a versus 33b

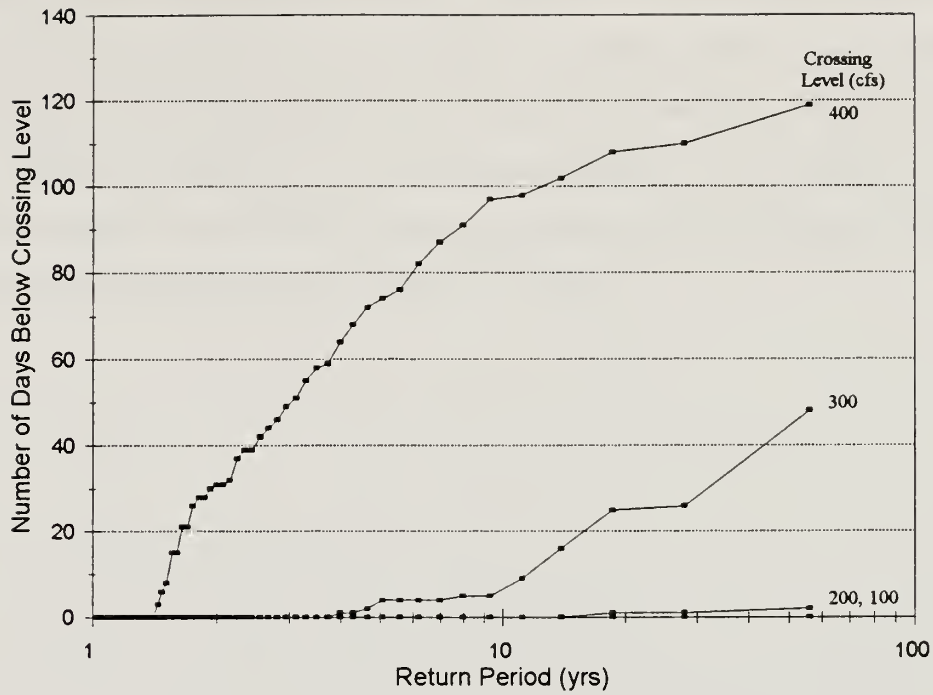

Fig.33a Duration of Low-Flow (Crossing Levels), Natural Conditions

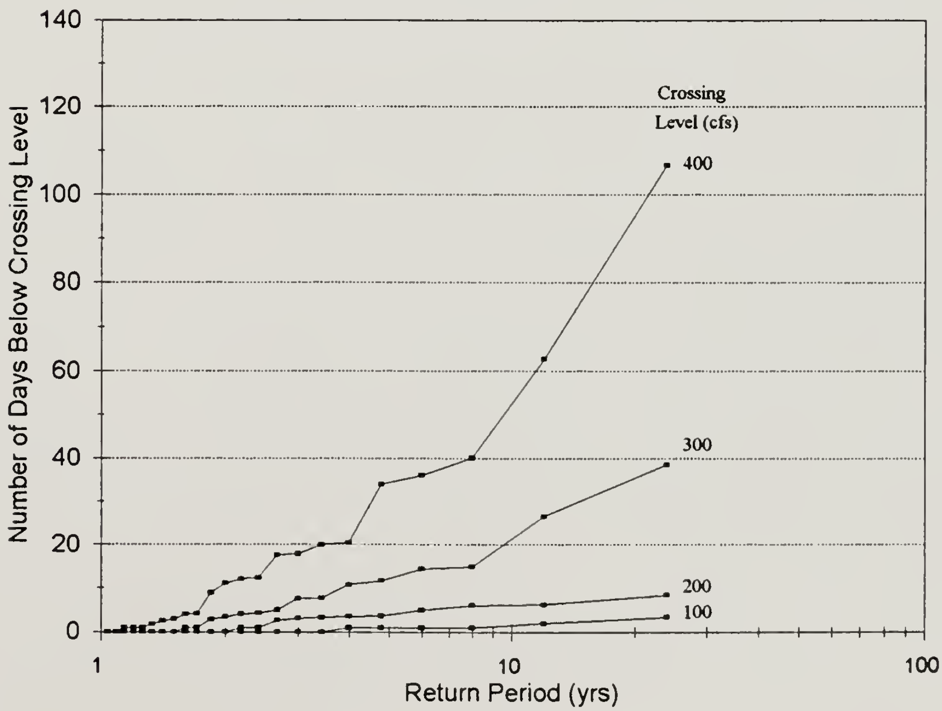

Fig.33b Duration of Low-Flow (Crossing Levels), After Diversion and Regulation

indicates a slight increase in the number of days in which flows fell below the 300, 200 and 100 cfs thresholds (for practically all return periods). In contrast to that, there is also a noticeable decrease in the deficit of the number of days with flows below 400 cfs and larger. This finding is a direct consequence of the low-flow augmentation effect produced by the reservoirs, and consistent with previously made observations about the impact of tunnel diversions and reservoir regulation on the series of low flows.

6.0 CHANGES IN FLOW VARIABILITY

The analysis presented in this Section corresponds to Scenario IV. It is aimed at quantifying the change in flow variability in the Gunnison River at BLCA introduced by the intervening inflows between Morrow Point Dam and Crystal Dam. As described in Section 2.5, these inflows are also referred to as Cimarron River/Crystal Creek discharges since these are the two major tributaries between the reservoirs. The analysis was conducted for water-years 1978 to 1993 primarily using data supplied by the Bureau of Reclamation. Refer to Section 2.5 for a detailed discussion concerning the reliability of the data used in this analysis.

6.1 Impact on the Variance of Daily Flows

The variance of a given time series is the simplest and most currently used statistic in hydrology to measure flow variability. The variance of mean-daily flows should be interpreted as a measure of the dispersion or spread of the daily flow values contained in the series about their mean. The variance s^2 of all aggregated daily flows over the entire 16 year period was calculated at several locations along the Gunnison River as indicated in Figure 7. Starting at Morrow Point and moving downstream in the river, the sites are: F16: releases from Morrow Point Dam, F9+F10: lateral inflows from Cimarron River and Crystal Creek combined, F18: total inflows to Crystal Reservoir, F17: releases from Crystal Dam and F13: Gunnison River flows at the entrance to the Black Canyon. Estimates of flow variance for all these locations along the Gunnison River allow us to quantify the incremental changes in flow variability introduced by each of the structures in the river, and ultimately, compare the present level of flow variability at BLCA with the estimated variability under natural conditions. The dispersion characteristics of a flow series can also be conveniently expressed in terms of the dimensionless coefficient of variation Cv, obtained as the ratio of the standard deviation to the mean, having different properties than s^2. The coefficient of variation is the most useful parameter for purposes of comparison of variability at two different sites. The computed values for both parameters at the different river sites are illustrated in Figure 34.

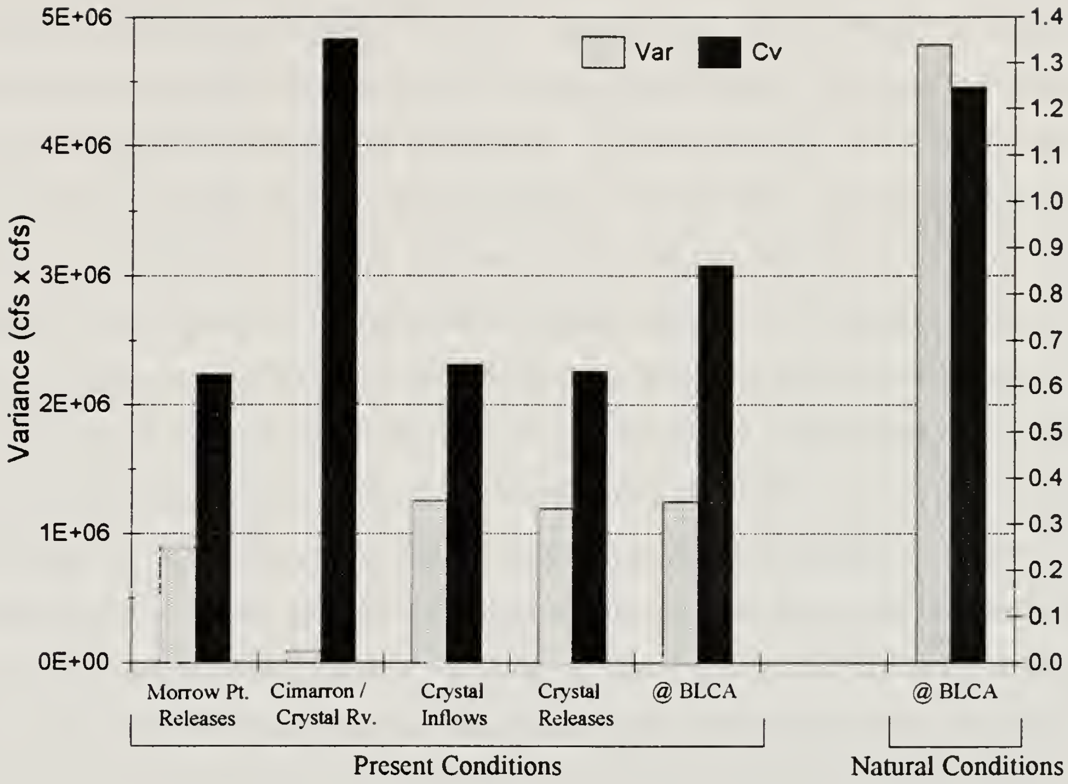

Fig.34 Incremental Changes in Flow Variability Along the Gunnison River

The first flow series under consideration, Morrow Point releases, displays a variance of 891,292 cfs^2 and coefficient of variation equal to 0.63. The variability of this flow series is heavily affected by consecutive regulation at Blue Mesa and Morrow Point reservoirs. The next pair of bars shown in Figure 34 corresponds to the intervening inflows between Morrow Point and Crystal Dams. These near natural lateral inflows show a small variance, 88408 cfs^2, compared to the variance of the flows released by Morrow Point Dam. However, when the influence of the two different means is excluded, the Cimarron River/Crystal Creek flow combination displays a much larger relative variation of flows as indicated by *Cv*, which increases from 0.63 to 1.35.

After the regulated and unregulated flows mix, they become inflows to Crystal Reservoir. The addition of the Cimarron River/Crystal Creek discharges to the Morrow Point releases increases the daily flow variance in the Gunnison River by roughly 40 percent,

however, the contribution of unregulated inflows barely increases the relative variability of flows in the Gunnison River from 0.63 to 0.65. Nevertheless, after flows are re-regulated by Crystal Reservoir, the flow variance and *Cv* decrease slightly again, returning to practically the same values computed for Morrow Point releases. The next structure in line is the Gunnison Tunnel which diverts water from the river according to the monthly distribution shown in Figure 10. As expected, the variance of flows at site 13 (labeled @ BLCA in Figure 34) essentially does not change (s^2 is unaffected when only changes in the mean flow occur), although *Cv* increases significantly, from 0.63 to 0.86, given the reduction in the mean flow.

In summary, while the addition of the unregulated lateral inflows between the two reservoirs increase the variance of the daily flows through the Black Canyon, this increase does not bring the variance even close to the historical levels under natural conditions. This is also demonstrated by Figure 34, where the right-end of the graph shows the characteristics of the flows under natural conditions at site F11 during the period 1911-1965, prior to the operation of the Aspinall Reservoirs and exempted of Tunnel diversions. The variance at BLCA under present conditions, 1,246,009 cfs^2, is only a 26% of the flow variance under unperturbed conditions, 4,782,285 cfs^2. The Gunnison Tunnel actually causes a considerable increase in the coefficient of variation (due to the decrease in mean flows), though again not up to historical levels before the tunnel and the reservoirs were built. Figure 34 also indicates that the *Cv* for the Cimarron River/Crystal Creek inflows is very similar to the value for the historical flows at BLCA (1.35 and 1.25 respectively), both of which are mostly, though not entirely, unregulated flows. This helps confirm that the results from this analysis, though not entirely based on completely reliable data, appear to be very reasonable.

6.2 Variance-Covariance Structure of Crystal Reservoir Inflows

In order to more fully understand the extent to which the Cimarron River/Crystal Creek inflows alter the variance of flows in the reach of the Gunnison River located between Morrow Point Dam and Crystal Dam, we will look at the individual components comprising the total variance of the flows. Figure 35 below indicates that the releases from the Morrow Point Dam (1) plus the natural flows from the intervening watershed (2) conform the total inflows to

Crystal Lake (3). Mathematically, the variance of the total inflows to Crystal Reservoir is desegregated into three components: the variance from the Morrow Point releases *Var(1)*, the variance from the intervening inflows *Var(2)*, and the covariance between these two series *Cov(1,2)*. The components are related by the following expression,

$$Var(3) = Var(1) + Var(2) + 2\ Cov(1,2)$$

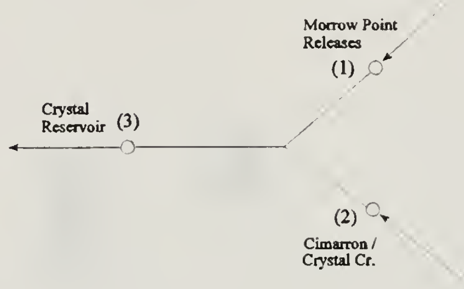

Fig.35 Schematic of Crystal Reservoir Inflows

After aggregating daily flows into twelve monthly intervals, the above equation was solved separately for each month to find the three components of the variance of the daily inflows to Crystal Reservoir. The components of the total variance for each month are illustrated as stacked bars in Figure 36. As illustrated in Figure 36, the contribution to the variance of the Gunnison River dispensed by the unregulated flows from the Cimarron River and Crystal Creek occurs almost exclusively during the higher runoff months, May through July, the snowmelt season. Furthermore, the increase in variance during these months is mostly a result of the covariance between the two flow series rather than the variance added by the intervening inflows per se. In turn, this covariance term can also be further broken down into its three multiplicative components as follows,

$$Cov(1,2) = \rho\ [Var(1)\ .\ Var(2)]^{1/2}$$

where the only new parameter is $\rho(1,2)$, the sample correlation coefficient between series (1) and (2). ρ is also a dimensionless dependence parameter that measures the degree of linear association between the two series. If series (1) and (2) were linearly independent, their

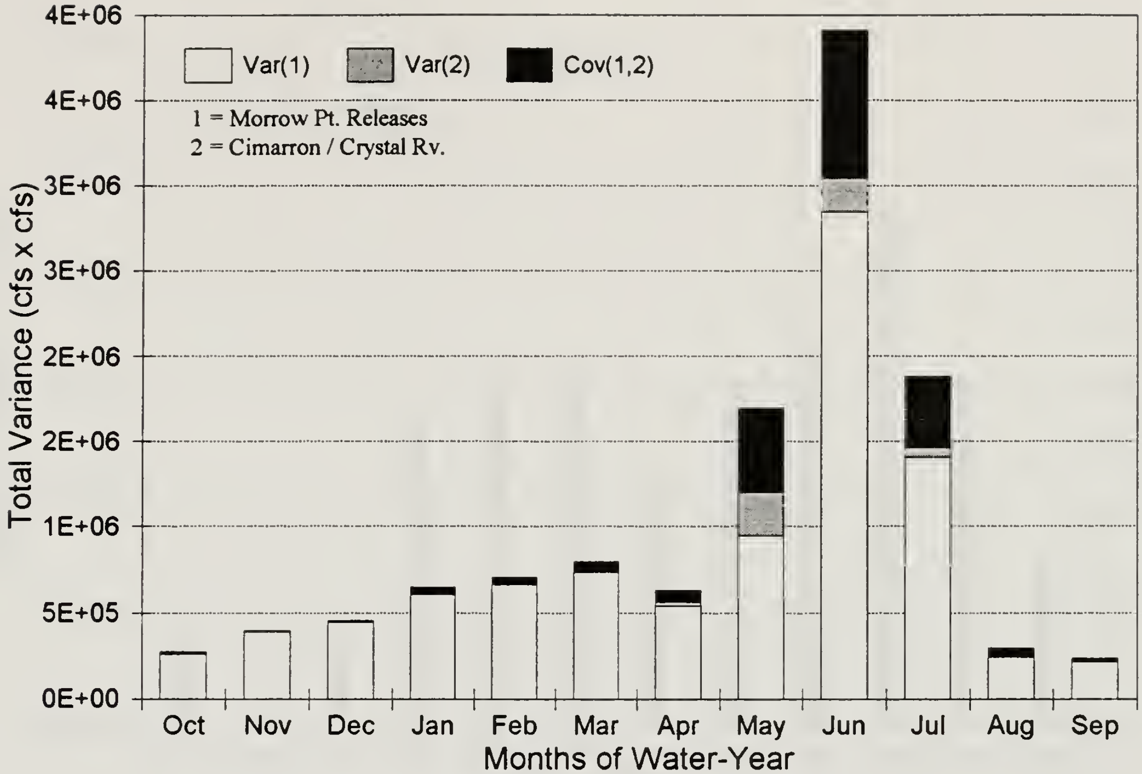

Fig.36 Variance Components for Crystal Reservoir Inflows

covariance would be zero. Again, the three components of the covariance of the grouped daily inflows were computed month by month, and the results shown in Figure 37.

The monthly variation in the correlation coefficient shown in Figure 37 is a direct consequence of the differences in flow pattern between the regulated (1) and unregulated (2) flows for that particular reach of the Gunnison River. See Figure 23 as an example of the potential differences in flow regime between the two sources of flows. Again, for the months of May, June and July in which the covariance term becomes significant, the variance of Morrow Point releases is a much larger component than the variance of the intervening inflows.

6.3 Analysis of the Time Dependence Structure of Daily Flows

In addition to the flow variance and the spatial correlation analysis presented in Section 6.2, the comparison of the time dependence structure of the impacted versus the natural flow series is investigated in this section. The time dependence of a time series is computed by

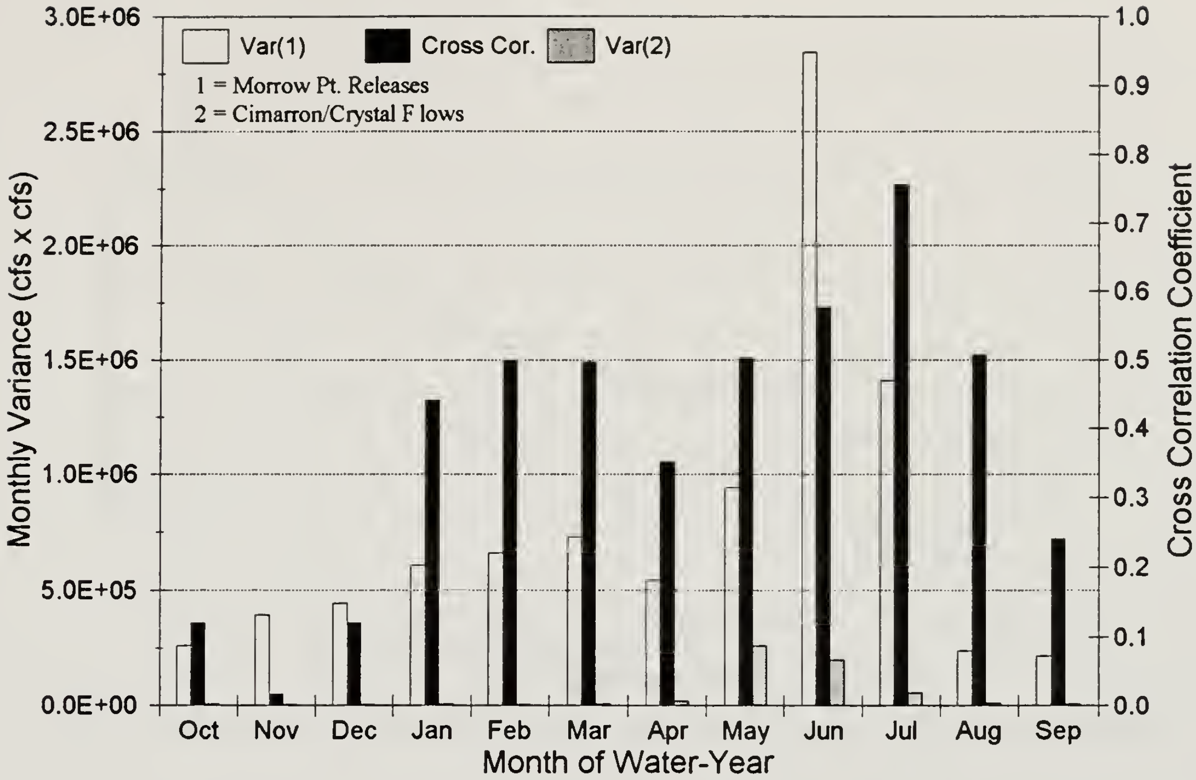

Fig.37 Covariance Components for Crystal Reservoir Inflows

means of the k^{th} autocorrelation coefficient r_k, where k denotes the lag adopted to investigate the dependence structure of the series. The most important case is for $k=1$, named the first autocorrelation coefficient r_1, which measures the linear association between flows from consecutive days. The same analysis performed for flows two days apart will result in the correlation coefficient for a lag of two, r_2. When this process is repeated for all lag intervals of interest and then each correlation coefficient is plotted versus the corresponding lag, the resulting curve is known as the correlogram. Correlograms were constructed for flows entering the Black Canyon area under impacted conditions (flow regulation and diversions) and natural conditions, which are presented in Figure 38. Both flow series were standardized to remove the periodicity in the mean and standard deviation of the series previous to computing the correlograms of the residual series in the transformed log-domain.

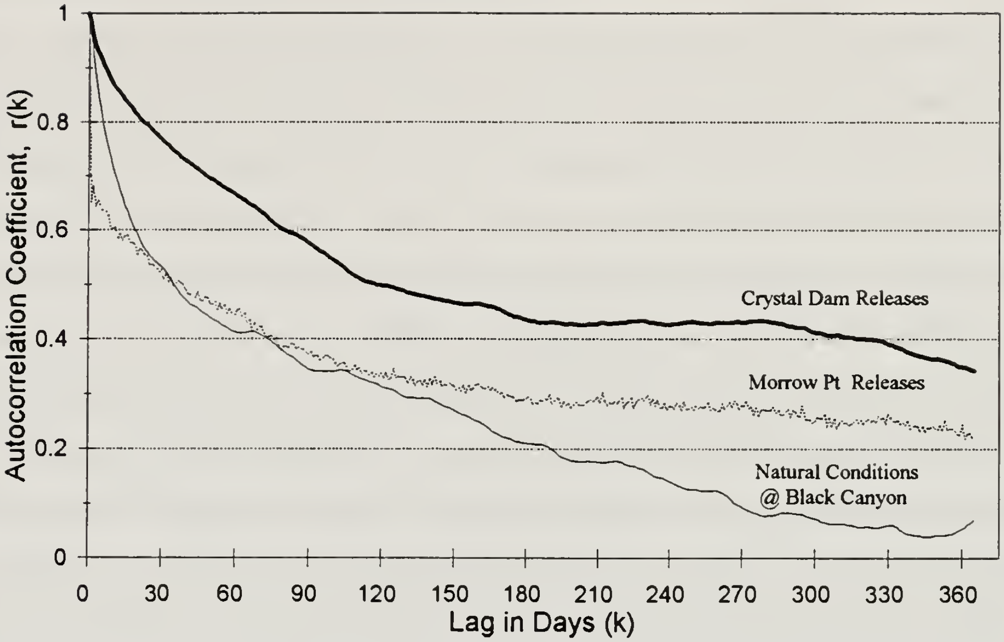

Fig.38 Correlograms of Standardized Series of Daily Flows, Natural and Present Conditions

There is a high contrast in the flow dependence structure between the regulated and unregulated series. While the correlogram for the natural series shows the typical shape of a natural flow regime in the Rocky Mountains, the human-impacted series shows a larger persistence of flows as indicated by the lower decaying rate of its correlogram. The slow decay of the impacted series is characteristic of a hydrologic system with long water storage memory, artificially created by the Aspinall Units. Additionally, Figure 38 shows the correlogram for the series of releases from Morrow Point Dam. It is interesting to compare the effect that the contrasting operational policies of the two reservoirs have in the correlograms. Morrow Point is operated as a peaking-power hydro plant, whereas Crystal only re-regulates the incoming flows to produce a smoother hydrograph at the end of the hydro-system. This is clearly reflected by the correlograms in Figure 38. The alternating high and low flows produced by the turbines at Morrow Point cause a sharp decrease in the correlation structure of the flows, particularly for the lowest lags. In contrast, the more uniform pattern of flow releases from Crystal Dam is reflected by the smooth decay of its correlogram, where low flows are mostly followed by low values, and conversely, high flows are followed by high flows, eliminating the natural fluctuation of high and low flows.

7.0 SUMMARY AND CONCLUSIONS

While many factors have contributed to the changes in the flow regime through the Black Canyon of the Gunnison River over this century, the two largest factors include the Gunnison Tunnel and the Aspinall Reservoirs. A detailed hydrologic analysis of the flows in the Gunnison River was conducted to quantify the extent to which each individual structure, as well as both structures together have impacted the natural flow conditions. In addition, an analysis was carried out to determine whether unregulated flows from the Cimarron River and Crystal Creek tributaries help to restore the natural variability of flows through the Black Canyon. The results of these analyses are summarized in the tables presented below.

These tables compare the values of each hydrologic variable determined for each of the scenarios analyzed. The first column with flows statistics in each table represents what flows under *Natural Conditions* through the Black Canyon between water-years 1911 to 1965 would have been without the effects of the tunnel diversions (reservoirs did not exist during that period except for Taylor park Reservoir, see Appendix B). The next column with flow statistics corresponds to flow conditions under the combined effect of both structures, tunnel and reservoirs, representing *Present Conditions* through the Black Canyon since water-year 1971 to the present. The following column, labeled *Difference*, indicates the percent change (and direction of change) of each of the flow statistic when going from natural to present conditions. Additionally, the last two columns, labeled *Tunnel Only* and *Reservoirs Only*, indicate the value of the flow statistics had each one of these structures were the only structure altering the natural flow regime.

7.1 Summary of Changes at the Annual Level

The first summary table, Table 3, compares the changes in the hydrology at the annual level. Results from this part of the study determined that the mean annual volume of flow through the Black Canyon has been reduced by approximately 30 percent from historical levels. While roughly half of this reduction is due to diversions through the Gunnison Tunnel, the other half occurred during a downward shift in flows in the Gunnison River after 1930.

Several factors have likely combined to cause this downward shift in the early 1930's, such as a decrease in precipitation, changes in land use practices and an increase in diversions within the basin, though the relative contribution of each factor is unknown. Furthermore, the standard deviation of these annual volumes was increased, which appears to be about equally due to the tunnel and the reservoirs.

In addition to volumes, low flows through the Black Canyon have been significantly reduced as a result of the diversions through the Gunnison Tunnel. Releases from the Aspinall Reservoirs have offset some of the low flow reductions, though this increase has not brought low flows back up to their natural levels. These conclusions were confirmed for each of the hydrologic analyses performed on the tunnel and the reservoirs. In contrast to the annual minimum flows, the significant reduction in the annual maximum flows was mostly caused by the operation of the reservoirs in which high flows are generally stored for later release. The contribution of the tunnel diversions to the reduction in high flows was relatively minor compared to the impact of the reservoirs.

Table 3. Summary of Annual Statistics

Hydrologic Variable	Natural Conditions (1911-65)	Present Conditions (1971-93)	Difference (%)	Tunnel Only (1911-1965)	Reservoirs Only (1971-93)
Mean Vol (ac-ft)	1,269,363	886,077	-30.2	1,007,700	1,213,965
St Dev Vol (ac-ft)	377,473	465,619	+23.4	428,072	432,512
Min Flow (cfs)	349.8	255.0	-27.1	48.6	369.2
Max Flow (cfs)	9,553	3,552	-62.8	9,134	3,957

Also at the annual level, Table 4 summarizes the changes in the magnitude-frequency relation of the discharge volumes, minimum flows and maximum flows. Only those quantiles associated with a return period of 2-year and 8-year are reported in this table for each of the three variables. The combined operation of the tunnel and the reservoirs caused a reduction in

the value of each hydrologic variable that would occur, on the average, once every two or eight years. This analysis confirms that the tunnel is responsible for the reduction in minimum flows, which was partially offset by the operation of the reservoirs. Also, the reservoirs were almost entirely responsible for the reduction in annual maximum flows.

Table 4. Summary of Annual Quantiles

Hydrologic Variable	Return Period (yrs)	Natural Conditions (1911-65)	Present Conditions (1971-93)	Difference (%)	Tunnel Only (1911-65)	Reservoirs Only (1971-93)
Mean Vol (ac-ft)	2	1,293,200	786,100	-39.2	1,040,100	1,103,900
Mean Vol (ac-ft)	8	1,731,700	1,383,400	-20.1	1,565,900	1,770,400
Max Flow (cfs)	2	10,100	2,740	-72.9	9,760	3,163
Max Flow (cfs)	8	13,700	5,300	-61.3	13,500	5,832
Min Flow (cfs)	2	340	264	-22.4	16	301
Min Flow (cfs)	8	460	65	-85.9	1.5	109

7.2 Summary of Changes at the Daily Level

Mean daily flows have been significantly reduced during the high runoff season and increased during the low runoff season. As a result, the natural snowmelt driven annual hydrograph has been converted to a fairly level curve so that the distribution of flow within each water-year is currently much different. Changes in the basic flow statistics of the daily time series are summarized in Table 5. The reduction in mean daily flows is the same reduction that was previously determined for the mean annual volumes. The standard deviation of the mean daily flows was slightly increased as a result of the tunnel operation more than the reservoir operations. In turn, the coefficient of variation, which is the ratio of

the standard deviation to the mean flow, nearly doubled, which again was mostly due to the Gunnison Tunnel causing a decrease in the mean and simultaneously an increase in the standard deviation. The dependence structure of natural flows from the snowmelt runoff in the Gunnison Basin is noticeably increased by the operation of the reservoirs. Figure 38 has shown the high contrast in autocorrelation for several lag-periods between the natural flows and the impacted flow series as a result of the regulation and successive re-regulation of flows by the reservoirs. Moreover, it was found that the periodic autocorrelation for only the lowest lag ($k=1$), was slightly reduced from 0.95 to a value of 0.92, for the combined effect of tunnel diversions and reservoirs regulation, although it was confirmed that the tunnel diversions had almost no effect.

Table 5. Summary of Daily Statistics

Daily Flow Statistic	Natural Conditions (1911-65)	Present Conditions (1971-93)	Difference (%)	Tunnel Only (1911-65)	Reservoir Only (1971-93)
Mean Flow (cfs)	1,753	1,220	-30.2	1,392	1,676
Stand. Dev. (cfs)	840.4	914.3	+8.8	917.1	875.0
Coefficient of Variation	0.383	0.737	+92.4	0.668	0.507
Autocorrelation Coefficient	0.952	0.923	-3.1	0.953	0.924

Next, the results of the flow-duration analysis are presented in Table 6. Annual flow-duration curves for a "typical" water-year were determined using the median values. As indicated by Table 6, the high flows (those exceeded the lowest percent of the time) were affected the most, primarily due to the storage of peak flows by the reservoirs. Mid-range flows, exceeded between about 40 to 80 percent of the time, were increased somewhat, which is entirely due to the gradual release of the peak flows stored in the reservoirs. Finally, the low flows (those exceeded most of the time) were reduced, though not as much as they would have been if not for the flow-augmentation effect introduced by the reservoirs.

Table 6. Summary of Daily Flow-Duration Analyses

Percent of Time Flow (in cfs) is Exceeded (%)	Natural Conditions (1911-65)	Both Structures (1971-93)	Difference (%)	Tunnel Only (1911-65)	Reservoir Only (1971-93)
1	9,135	2,650	-71.0	8,440	2,887
5	6,983	2,480	-64.5	6,435	2,628
10	5,220	2,035	-39.0	4,440	2,508
20	2,720	1,750	-35.7	2,070	2,045
40	1,100	1,170	+6.4	600	1,540
60	611	757	+23.9	450	1,237
80	432	440	+1.9	340	1,117
90	400	349	-12.8	180	934
95	380	309	-18.7	72	767
99	360	264	-26.7	22	98

The results of the high- and low-flow frequency analyses are presented in Table 7 and Table 8, respectively. Only three of the six *n*-day intervals are listed which are again associated with the 2- and 8-year return periods. As expected, the average *n*-day high flows are reduced by the reservoirs while the average *n*-day low flows are reduced by the tunnel.

Table 7. Summary of *n*-Days High-Flow Frequency

n-Days	Return Period (yr)	Natural Conditions (1911-65)	Present Conditions (1971-93)	Difference (%)	Tunnel Only (1911-65)	Reservoir Only (1971-93)
3	2	9,833	2,720	-72.3	9,102	2,979
	8	13,600	4,800	-64.7	13,333	5,365
7	2	8,274	2,581	-68.8	8,025	2,774
	8	13,071	4,767	-63.5	12,729	5,332
30	2	6,936	2,251	-67.5	6,046	2,479
	8	10,000	3,880	-61.2	9,553	4,642

Table 8. Summary of *n*-Days Low-Flow Frequency

n-Days	Return Period (yr)	Natural Conditions (1911-65)	Present Conditions (1971-93)	Difference (%)	Tunnel Only (1911-65)	Reservoir Only (1971-93)
3	2	350	275	-21.4	18	329
	8	263	99	-62.4	3	187
7	2	361	282	-21.9	25	477
	8	291	113	-61.2	5	218
30	2	383	325	-15.1	82	773
	8	320	194	-39.4	30	305

The last two summary tables list the results of the high- and low-flow crossing level analyses are summarized in Table 9 and Table 10 respectively. As before, only those durations associated with a return period of 2-year and 8-year were chosen for reference. In general, the number of days in which the high-flow thresholds were exceeded during an average two or eight years period was reduced almost exclusively by the reservoirs. On the other hand, the number of days in which flows fell below the low-flow thresholds for the same recurrence intervals was significantly increased by the tunnel operation.

Table 9. Summary of High-Flow Crossing Level Analysis

Threshold (cfs)	Return Period (yr)	No.of Days Natural Conditions (1911-65)	No.of Days Both Structures (1971-93)	Difference (x times)	No.of Days Tunnel Only (1911-65)	No.of Days Reservoirs Only (1971-93)
15000	2	0	0	0	0	0
	8	0	0	0	0	0
12500	2	0	0	0	0	0
	8	5	0	≈-5	5	0

10000	2	1	0	≈-1	0	0
	8	15	0	≈-15	12	0

Table 10. Summary of Low-Flow Crossing Level Analysis

Threshold (cfs)	Return Period (yr)	No.of Days Natural Conditions (1911-65)	No.of Days Present Conditions (1971-93)	Difference (x times)	No.of Days Tunnel Only (1911-65)	No.of Days Reservoirs Only (1971-93)
100	2	0	0	0	20	0
	8	0	3	≈+3	85	0
200	2	0	0	0	42	0
	8	0	44	≈+44	128	2
300	2	0	13	≈+13	57	0
	8	5	146	+29	145	26
400	2	31	71	+2.3	109	4
	8	91	314	+3.5	224	85

Finally, results from Scenario IV that analyzed changes in flow variability upstream from the Black Canyon indicates that the inflows to the Gunnison River discharging from the Cimarron River and Crystal Creek tributaries increase only marginally the variability of flows in the Gunnison River after being regulated by the Blue Mesa and Morrow Point reservoirs. The resulting variance of the flows at BLCA under present conditions is only a 23 percent of the flow variance under natural conditions. This substantial decrease in flow variability, due mostly to the presence of the reservoirs, was confirmed using a dimensionless descriptor of flow variability such as the coefficient of variation.

8.0 LITERATURE CITED

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Appendix A : Summary of Analysis Tools

Periodic Mean, $\boldsymbol{m_t}$

$$m_t = \frac{1}{n} \sum_{\nu=1}^{n} X_{\nu,t}$$

where $X_{p,t}$ represents the observed daily values, with $\nu=1,2,...n$ the sequence of years of record, and $t=1,2,...,w$ the sequence of days in the annual cycle of $w=365$,

Periodic Standard Deviations, s_t

$$s_t = \left[\frac{1}{n-1} \sum_{\nu=1}^{n} (X_{\nu,t} - m_t)^2 \right]^{1/2}$$

where all variables are as defined above.

Periodic Coefficient of Variation, $\boldsymbol{Cv_t}$

$$Cv_t = \frac{s_t}{m_t}$$

computed as the ratio between the periodic standard deviation s_t and the periodic mean of the flows m_t as previously defined.

Periodic Correlation, $r_{k,t}$

$$r_{k,t} = \frac{\sum_{\upsilon=1}^{n} (X_{\upsilon,t} - m_t)(X_{\upsilon,t-k} - m_{t-k})}{\left[\sum_{\upsilon=1}^{n} (X_{\upsilon,t} - m_t)^2 \sum_{\upsilon=1}^{n} (X_{\upsilon,t-k} - m_{t-k})^2 \right]^{1/2}}$$

the linear dependence of flows is measured by the k^{th} correlation coefficient r_k, where k indicates the lag (in days) to measure the degree of association between flow values. The rest of the variables have been previously defined.

Variance, Var_X

$$Var_X = \frac{1}{n-1} \sum_{v=1}^{n} (X_v - m_X)^2$$

where m_X is the mean of the seriea X under analysis, and all other parameters are as defined above.

Covariance, $Cov_{(X,Y)}$

$$Cov\,(x,y) = \frac{1}{n} \sum_{v=1}^{n} (X_v - m_X)(Y_v - m_Y)$$

where m_X and m_Y are the mean of the series X and Y respectively. All other parameters are as defined above.

Correlogram, r_k

$$r_k = f(k)$$

r_k is computed as a function of the lag k only, and by means of the same equation used to compute the periodic correlation, except that the time index t is dropped.

Appendix B : Effect of Taylor Park Reservoir

A point of special consideration when analyzing the streamflow data for "Scenario I: Gunnison Tunnel", was the potential effect that regulated releases from Taylor Park Reservoir (TPR) might have in the flow regime at BLCA during the sub-period 1937-1965, that is, after TPR started regulating flows in 1937. It should be remembered that in Section 2.2 of this report (page 10), the effect of TPR on the natural flow regime at BLCA was assumed negligible for the purpose of analyzing Scenario I. The objective of this appendix is to demonstrate the validity of that assumption.

Taylor Park Dam is located in the headwaters of the Gunnison Basin, impounding water from the Taylor River, near the continental divide (Hydrologic Unit 14020001 in Figure 1). The reservoir collects inflows from a drainage area of approximately 254 mi^2, which represents a 6.4% of the total area of the basin measured near the entrance to BLCA. This upper basin reservoir stores water during the snowmelt season, from mid April to the end of June, to be released latter during the months of July through October, the months with the highest demand for irrigation water in the Uncompahgre Valley (see Figure 10). Augmentation of flows in the Gunnison River during the last portion of the irrigation season had the objective of incrementing diversions of water into the Gunnison Tunnel. Figure B.1 compares two mean annual hydrographs (in dimensionless form) at the dam site (F21), before and after Taylor Reservoir

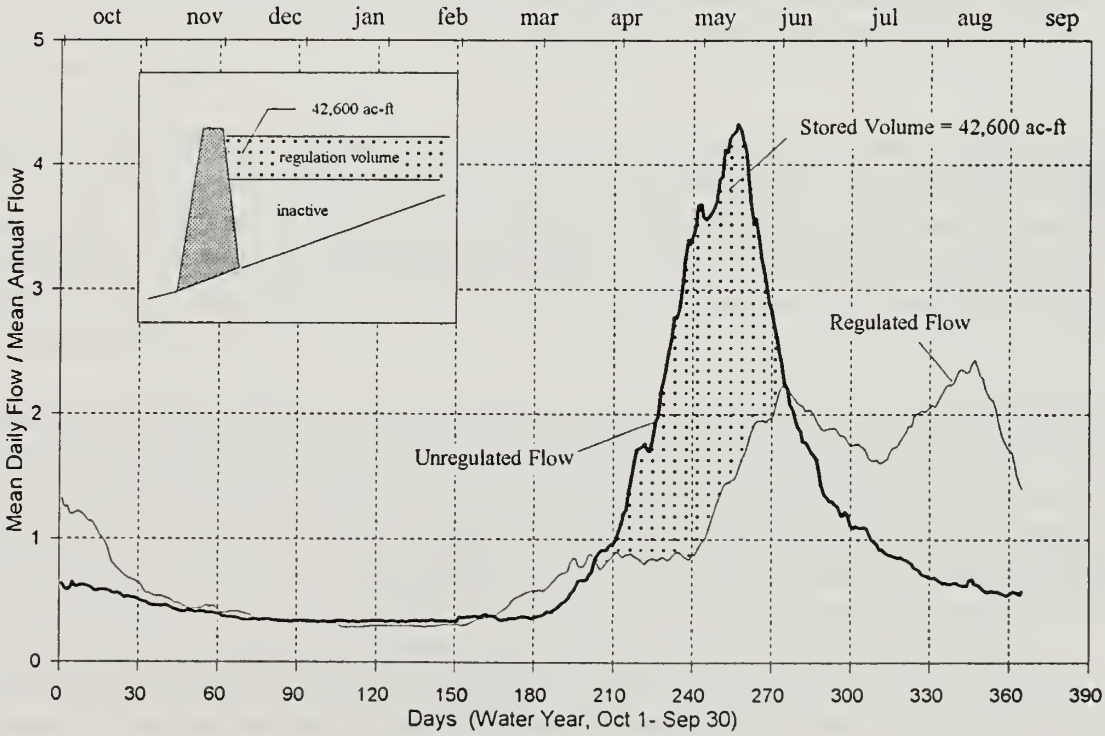

Fig.B.1 Hydrographs at Taylor Park (site F21) before and after flow regulation (1937)

began operating in 1937. We can easily observe the differences in seasonality of the two hydrographs, obviously attributed to the regulation effect of the reservoir.

Based on historical flow records available in the Taylor River, it can be estimated that the average volume of water stored in the reservoir every year (indicated by the dotted area between the two hydrographs) amounts to 42,600 ac-ft. This volume is considerable lower than the reported total storage capacity of the reservoir of 106,200 ac-ft. In other words, the regulation pool at the reservoir is only 40% of its total capacity. Another index, the ratio of the reservoir regulation volume over the mean annual discharge of the river, gives an indication of the relative regulation capacity of a reservoir. This ratio is equal to 0.3 at the Taylor Dam site, and only 0.03 when the regulation storage of Taylor Reservoir is compared with the total flow measured at BLCA.

The effect of flow regulation at TPR in the flow regime at BLCA was investigated at three different levels: annual, seasonal and daily time intervals. Starting at the annual level, a double mass curve analysis was performed using annual discharges from two adjacent watersheds: the East River catchment at station F19 (almost natural conditions) and the Taylor River catchment at station F20 (24 miles downstream from TPR) . The two gaging sites are located at practically the same elevation, have the same annual discharge, and the hydrographs for both catchments are dominated by the same snow accumulation and melting processes. The analysis showed no change in slope of the double mass curve for the sub-periods before and after 1937 (for a total of 71 years). This indicates that there is no apparent multi-year carryover storage in the reservoir. In other words, the volume stored in the reservoir during the spring is released that same year during the summer months.

The local effect of flow regulation at TPR in the seasonal series of flows is clearly exposed in Figure B.1. The single peak of the hydrograph occurring during the snowmelt season is shifted later toward the summer months. Furthermore, the amplitude of the peak is reduced to practically half of the magnitude corresponding to unregulated flows. The period with the lowest flows, from November through March, shows practically no change. This is an important finding when analyzing minimum flows at BLCA.

Since flows measured at site F21 represent, on average, only an 11% of the total discharge measured at site F11 (BLCA) during the same period, we should expect to see a gradual attenuation of the regulating effect of TPA in the Gunnison River flows as we travel downstream, from the Taylor Park Reservoir area to the Black Canyon Monument area. For that purpose, we present in Figure B.2 a schematic of the Gunnison River, showing the location of the flow gaging sites F21 (254 mi^2), F20 (477 mi^2), F1 (1012 mi^2) and F11 (3965 mi^2), listed in downstream order and with the accumulated drainage area shown in parenthesis. The sequential series of the dimensionless mean-daily hydrographs are displayed in a single graph, Figure B.3, in which the legend indicates the site number and the period of record considered for each hydrograph. The dramatic distortion of the hydrograph at site F21 (immediately downstream from TPR) becomes less and less accentuated as we move downstream. At site F1, upstream from the lake formed by

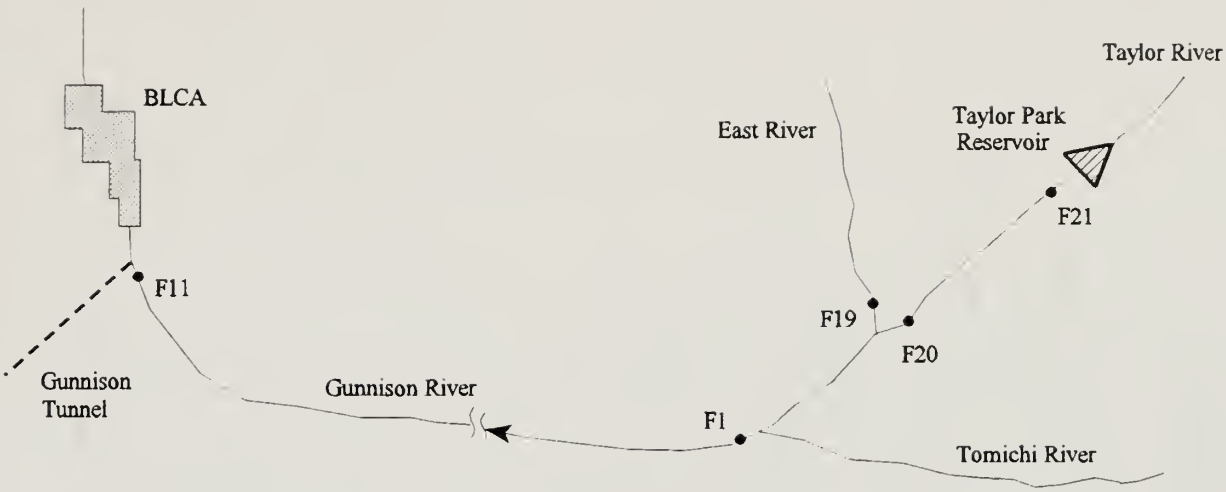

Fig.B.2 Schematic of the Gunnison River from TPR to BLCA

the Blue Mesa Reservoir since 1965, the hydrograph has already recuperated its natural shape, and by the time it gets to the BLCA area, only minor differences can be found when compared with flow conditions prior to 1936 (thicker curve).

A more detailed analysis of the effect of flow regulation at TPR was conducted by partitioning the historical flow records at site F11 into two subsamples, from 1911 to 1935 (before TPR), and from 1937 to 1965 (with flows regulated only by TPR). After a statistical analysis of the two sub-series indicated above, the following conclusions can be drawn:

- the frequency and magnitude of the highest-daily peaks at BLCA were practically unaffected by regulation at TPA.
- the series of minimum-daily flows at BLCA remained also unaffected for most of the year, except for the months of June through September, when they increased about 7 percent.
- the "n-day low-flows" frequency analysis indicated the same tendency already displayed in Fig.19 by the set of curves labeled "Natural" conditions. The curves developed from the 1911-1935 sub-period (without TPR) remained all above the "Natural" curves. For recurrence intervals less than 5 years, differences in flow ordinates between these two group of curves is around 10 percent. For higher recurrence intervals the differences are also higher. Is interesting to note that the derived curves from the 1911-1937 data set never fall below 300 cfs. Following the example in the last paragraph of page 32, we can add that had TPR not existed, the "Natural" 14-day low flow would have been 405 cfs (instead of 370). In other words, TPR is responsible for some decrease in low-flows at BLCA, although the greatest reduction (roughly 90%) is still attributed to the Gunnison Tunnel.
- the results from the low-flows "crossing level" analysis were very similar to those shown in Fig.20. The only difference being in the 300 cfs curve (under "Natural" conditions) which was practically never crossed (it remained together with the 100 and 200 lines next to the horizontal axis). Obviously, 300 cfs is a natural low-flow threshold for the watershed when measured at BLCA.

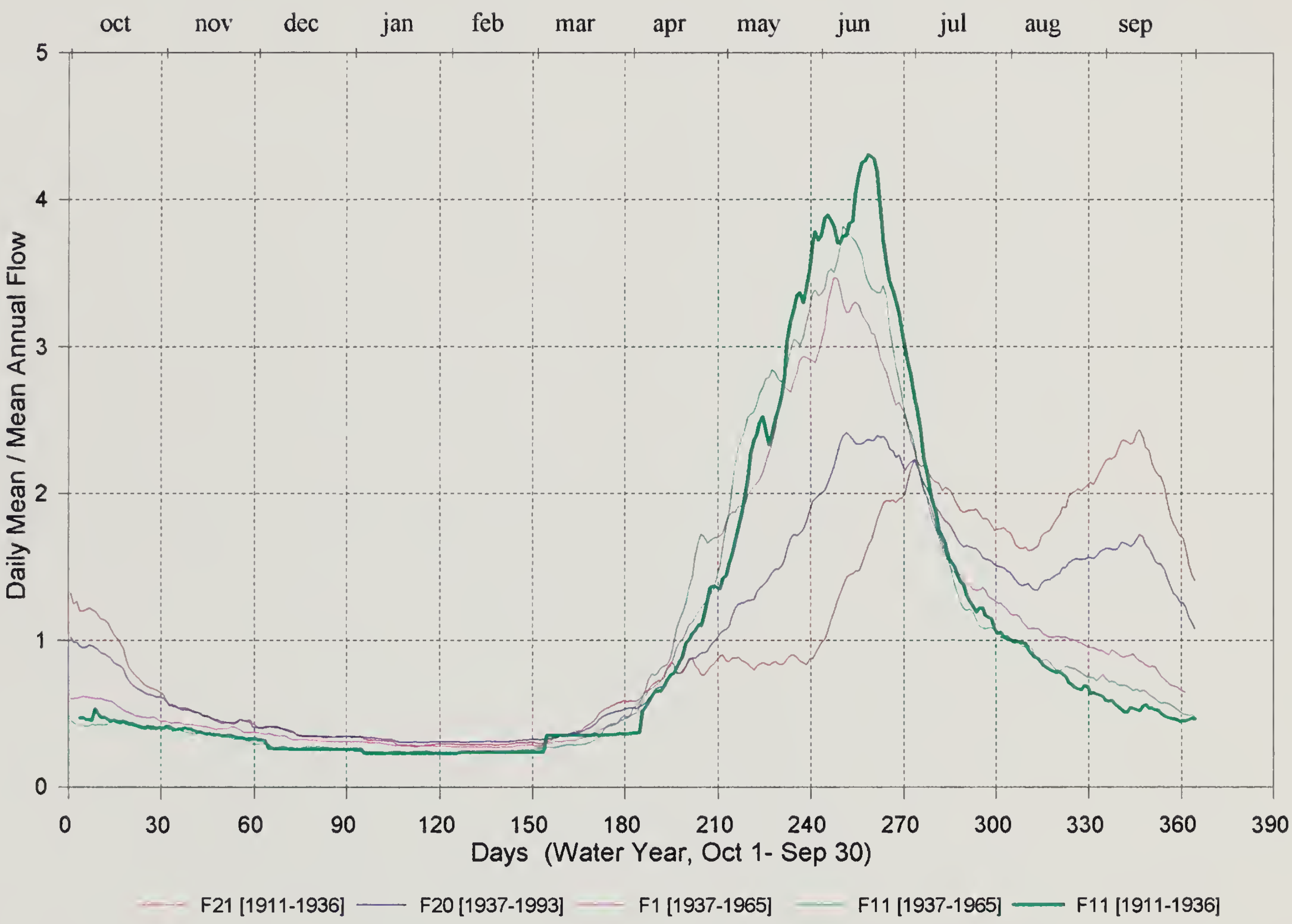

Fig.B.3 Mean Daily Hydrographs along the Gunnison River, from TPR to BLCA